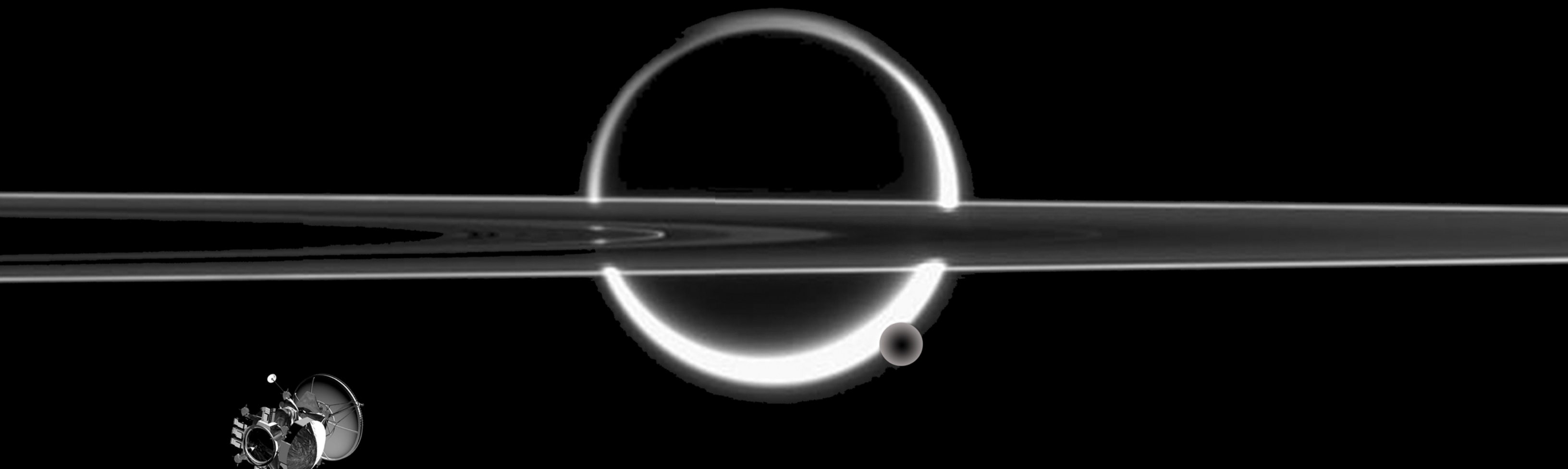
TSSM

Titan Saturn System Mission



Final Report

on the

NASA Contribution to a Joint Mission with ESA

January 30, 2009

Task Order #NM0710851

Titan Saturn System Mission Study
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Part of the research described in this report was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Research described in this report was also carried out at the Applied Physics Laboratory, Johns Hopkins University and at the European Space Agency.

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and Caltech.

Titan Saturn System Mission Study 2008: Final Report

Task Order #NMO710851

30 January 2009

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TABLE OF CONTENTS

Fact Sheet

Foreword

1.0 Executive Summary ... 1-1
- 1.1 Overview ... 1-1
- 1.2 Background ... 1-1
- 1.3 Study Approach ... 1-2
- 1.4 Science Overview ... 1-2
- 1.5 Mission Architecture Assessment ... 1-4
- 1.6 Mission Implementation ... 1-5
- 1.7 Cost, Schedule, and Risk ... 1-7
- 1.8 Summary and Conclusions ... 1-9

2.0 Science Goals and Objectives ... 2-1
- 2.1 The Relevance and Prominence of Titan Exploration ... 2-2
  - 2.1.1 Titan as an Organic-Rich Environment ... 2-2
  - 2.1.2 Titan as a Model for Planetary Climates with Rapid Loss of Volatiles ... 2-4
- 2.2 Science Background ... 2-4
  - 2.2.1 Geophysics ... 2-4
  - 2.2.2 Titan's Atmosphere ... 2-6
  - 2.2.3 Titan's Geology ... 2-9
  - 2.2.4 Titan's Organic Chemistry and Astrobiology ... 2-14
  - 2.2.5 Evolution and Interaction with the Saturn System ... 2-16
  - 2.2.6 Enceladus ... 2-17
- 2.3 Mission Goals, Science Objectives, and Investigations ... 2-20
  - 2.3.1 Introduction ... 2-20
  - 2.3.2 Key Questions to be Addressed by TSSM ... 2-21
  - 2.3.3 Structure of the Traceability Matrices ... 2-25
  - 2.3.4 Development of the Titan Mission Goals and Science Objectives ... 2-26
  - 2.3.5 Traceability from Guiding Documents ... 2-26
  - 2.3.6 Mission Goals and Objectives of TSSM ... 2-31
  - 2.3.7 Justification of the Science Investigations and the Required Measurements ... 2-32
- 2.4 Science Implementation ... 2-85
  - 2.4.1 Payload Considerations ... 2-86
  - 2.4.2 Planning Payload ... 2-87
  - 2.4.3 Measurement Approaches and Implementation ... 2-88
  - 2.4.4 Instrument and Mission Requirements ... 2-110
  - 2.4.5 Data Acquisition Strategy ... 2-111
  - 2.4.6 Science Operations and Planning ... 2-113
  - 2.4.7 Data Analysis and Archiving ... 2-118

2.5 Opportunistic Science with TSSM 2-119
2.5.1 Ring Science during Saturn Orbit Insertion 2-119
2.5.2 Saturn Atmospheric Science 2-120
2.5.3 Additional Icy Satellite Flybys 2-121
2.6 Synergy between the Orbiter and *In Situ* Elements 2-121
2.7 Primacy of the Orbiter 2-125
3.0 Mission Architecture Assessment 3-1
3.1 Introduction and Study Context 3-1
3.1.1 Constraints from the Study Charters 3-1
3.2 Architecture Selection 3-2
3.2.1 Selection Process and Criteria 3-2
3.2.2 Results and Summary 3-4
3.3 Architectural Options 3-5
3.3.1 Baseline Architecture Description 3-6
3.3.2 Alternate Architectures 3-8
3.3.3 Architecture Options Not Analyzed 3-9
4.0 Mission Concept Implementation 4-1
4.1 Mission Architecture Overview 4-1
4.1.1 Draft Level 1 Requirements (Science Only) 4-1
4.1.2 Key Driving Requirements 4-1
4.1.3 Baseline Mission Description 4-2
4.1.4 Floor (NASA/ESA and NASA-only) Mission Description 4-2
4.2 Science Investigation 4-3
4.2.1 Planning Payload 4-3
4.2.2 Instrument Descriptions 4-10
4.3 Mission Design Overview 4-31
4.3.1 Mission Phase Definitions 4-31
4.3.2 Launch 4-31
4.3.3 Interplanetary Trajectory 4-31
4.3.4 Saturn Tour Trajectory 4-34
4.3.5 Delivery of *In Situ* Elements 4-36
4.3.6 *In Situ* Element Relay 4-37
4.3.7 Titan Aerobraking 4-38
4.3.8 Titan Circular Orbit 4-41
4.3.9 Decommissioning and Disposal 4-41
4.3.10 Mission ΔV 4-42
4.3.11 Backup Launch Opportunities 4-43
4.3.12 Trajectory Modeling Assumptions 4-44
4.4 Flight System Design and Development 4-44
4.4.1 Flight System Overview 4-44
4.4.2 Systems Engineering 4-45
4.4.3 Subsystem Descriptions 4-56
4.4.4 SEP Stage 4-76

4.4.5 *In Situ* Element Accommodation 4-81
4.4.6 Verification and Validation 4-82
4.4.7 Completed Trade Studies 4-87
4.5 Ground System 4-89
4.5.1 Ground System Architecture 4-89
4.5.2 Ground System during the TSSM Mission 4-94
4.6 Operational Scenarios 4-95
4.6.1 Operating in Titan Orbit 4-95
4.6.2 Mission Scenarios Overview 4-96
4.6.3 Scenario Descriptions 4-100
4.6.4 Data Return Strategy 4-109
4.6.5 Data Processing and Science Planning 4-113
4.6.6 Mission Performance 4-114
4.7 Planetary Protection 4-117
4.7.1 Overview of Planetary Protection 4-117
4.7.2 PP Requirements 4-117
4.7.3 PP Technical Approach 4-117
4.7.4 Missions Operations 4-118
4.8 Selected Activities for Phase A Study 4-118
4.9 Technology Assessment 4-119
4.10 TSSM Risk Assessment 4-121
4.10.1 Mission Length 4-122
4.10.2 Launch Vehicle Logistics and Integration of RPS 4-123
4.10.3 NEXT Development 4-123
4.10.4 Radioisotope Power System Availability 4-124
4.10.5 Operational Complexity 4-124
4.10.6 Planetary Protection 4-125
4.11 Programmatics 4-125
4.11.1 Management Approach 4-125
4.11.2 Organization and Decision Making 4-126
4.11.3 Teaming 4-128
4.11.4 Roles and Responsibilities 4-128
4.11.5 Work Breakdown Structure 4-128
4.11.6 Schedule 4-130
4.11.7 Estimated Mission Cost 4-133
4.11.8 Risk Assessment and Management Strategy 4-141
4.11.9 NEPA Compliance and Launch Approval 4-143
5.0 Alternate Launch Opportunities 5-1
5.1 SEP Flight-Time Flexibility 5-1
5.2 Alternate Flight System Mission Designs 5-1
5.2.1 SEP Fallback Options 5-2
5.2.2 Chemical Fallback Options 5-2

6.0 Study Team Members and Roles ... 6-1
6.1 Team Overview ... 6-1
6.2 Jet Propulsion Laboratory Role ... 6-1
6.3 University of Arizona Role ... 6-4
6.4 Johns Hopkins University-Applied Physics Laboratory Role ... 6-4
6.5 National Aeronautics and Space Administration Role ... 6-4
6.6 European Space Agency Role ... 6-4
6.7 Centre National d'Etudes Spatiales Role ... 6-4
6.8 NASA Glenn Role ... 6-4
6.9 APL-JPL Outer Planets Steering Group ... 6-5
6.10 Study Results Review Process ... 6-5

APPENDICES

A Acronyms and Abbreviations ... A-1
B References ... B-1
C Telecommunications Link Analysis ... C-1
D Cost Detail ... D-1
E Flight System Design Supporting Detail ... E-1
F Previous Mission Studies ... F-1
G International Context ... G-1
H NEXT Thruster Technology for TSSM SEP Stage ... H-1
I Impact of *In Situ* Accommodation ... I-1
J European Space Agency *In Situ* Concept Implementation ... J-1
K Mission Operations Lessons Learned Study ... K-1
L Support to TSSM by Cassini Extended Extended Mission ... L-1
M Letters of Support and Commitment ... M-1
N Compliance Matrix ... N-1

FOLDOUTS

FO-1 Mission Design ... 4-33
FO-2 Flight System Block Diagram ... 4-52
FO-3 SEP Stage Details ... 4-79
FO-4 Orbiter Verification and Validation ... 4-86
FO-5 Total Data Return ... 4-99
FO-6 Master Schedule ... 4-132
FO-7 Cost ... D-49

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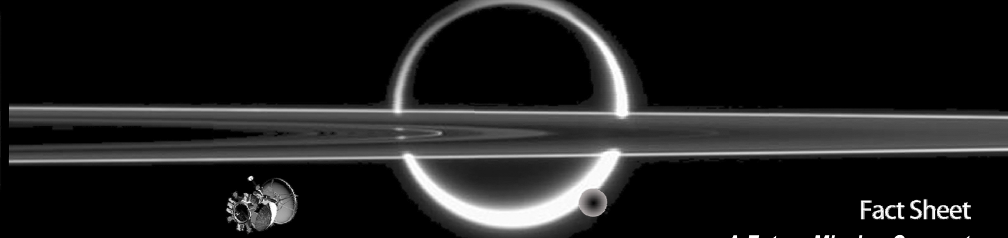
TSSM

Titan Saturn System Mission



Fact Sheet

A Future Mission Concept

Why TSSM?

Rugged shorelines, laced with canyons, leading to ethane/methane seas glimpsed through an organic haze, vast fields of dunes shaped by alien siroccos…

An icy moon festooned with plumes of water-ice and organics, whose warm watery source might be glimpsed through surface cracks that glow in the infrared…

The revelations by Cassini-Huygens about Saturn's crown jewels, Titan and Enceladus, have rocked the public with glimpses of new worlds unimagined a decade before. The time is at hand to capitalize on those discoveries with a broad mission of exploration that combines the widest range of planetary science disciplines—Geology, Geophysics, Atmospheres, Astrobiology, Chemistry, Magnetospheres—in a single NASA/ESA collaboration.

The Titan Saturn System Mission will explore these exciting new environments, flying through Enceladus' plumes and plunging deep into Titan's atmosphere with instruments tuned to find what Cassini could only hint at. Exploring Titan with an international fleet of vehicles; from orbit, from the surface of a great polar sea, and from the air with the first hot air balloon to ride an extraterrestrial breeze, TSSM will turn our snapshot gaze of these worlds into an epic film.

TSSM Science Goals & Objectives

Goal A: Explore Titan, an Earth-like System

How does Titan function as a system? How are the similarities and differences with Earth, and other solar system bodies, a result of the interplay of the geology, hydrology, meteorology, and aeronomy present in the Titan system?

Goal B: Examine Titan's Organic Inventory – A Path to Prebiological Molecules

What is the complexity of Titan's organic chemistry in the atmosphere, within its lakes, on its surface, and in its putative subsurface water ocean? How does this inventory differ from known abiotic organic material in meteorites and contribute to our understanding of the origin of life in the Solar System?

Goal C: Explore Enceladus and Saturn's Magnetosphere – Clues to Titan's Origin and Evolution

What is the exchange of energy and material between the Saturn magnetosphere, solar wind and Titan? What is the source of geysers on Enceladus? Does complex chemistry occur in the geyser source?

Planning Payload

Orbiter

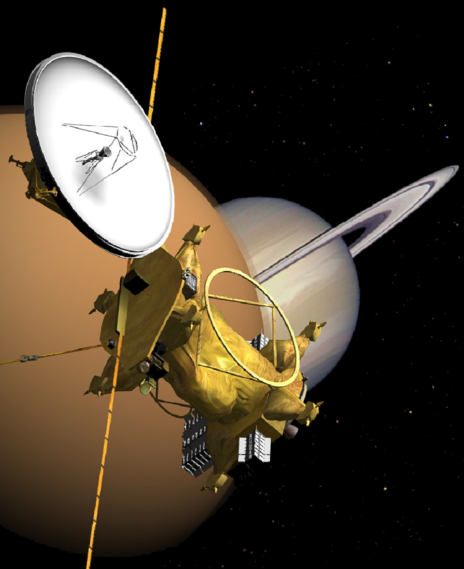
	Orbiter Planning Payload	Instrument Capabilities
HiRIS	High-Resolution Imager and Spectrometer (near IR)	1–6 µm global mapping at 50 m/pixel in three colors. Adjustable spectral editing for surface/atmosphere studies.
TiPRA	Titan Penetrating Radar and Altimeter	>20 MHz global mapping of subsurface reflectors with 10 m altitude resolution in altimetry mode & >10 m depth resolution. Lower data rate sounding mode with ~100 m depth resolution. ~1 km x 10 km spatial resolution.
PMS	Polymer Mass Spectrometer	TOF MS with M /ΔM ~10,000 for masses up to 10,000 Da. From 600 km to upper atmospheric *in situ* analysis of gases and aerosol precursors.
SMS	Sub-Millimeter Spectrometer	Heterodyne spectrometer with scanning mirror. Direct winds from Doppler and temperature mapping from ~200-1000 km altitude; carbon dioxide and nitrile profiles.
TIRS	Thermal Infrared Spectrometer	Passively cooled Fourier spectrometer, 7–333 µm. Organic gas abundance, aerosol opacity and temperature mapping 30–500 km.
MAPP	Magnetometer	Tri-axial fluxgate sensors. Noise level ~11pT$_{rms.}$ Interaction of field with ionosphere: internal and induced field.
	Energetic Particle Spectrometer	TOF Analyzer w/ss detectors to measure magnetospheric particle fluxes, ~10 keV to >MeV with 150° x 15° FOV.
	Langmuir Probe	Swept voltage/current probe. *In situ* electron density and temperature, ion speed constraint, including during aerosampling.
	Plasma Spectrometer	Electrostatic analyzer with Linear electric field TOF MS. Measures ion and electron fluxes at ~5 eV to ~5 keV. M/ΔM~10.
RSA	Radio Science and Accelerometer	All components part of spacecraft telecom system. Lower stratosphere and troposphere T profile. Gravity field.

Montgolfière

Montgolfière Planning Payload (10 km altitude in equatorial region)	
BIS	Balloon Imaging Spectrometer (1–5.6 µm)
VISTA-B	Visual Imaging System for Titan Balloon
ASI/MET	Atmospheric Structure Instrument/ Meteorological Package
TEEP-B	Titan Electric Environment Package
TRS	Titan Radar Sounder (>150 MHz)
TMCA	Titan Montgolfière Chemical Analyzer (1–600 Da Mass Spectrometer)
MAG	Magnetometer
MRST	Radio Science using spacecraft / montgolfière telecom system

Lander

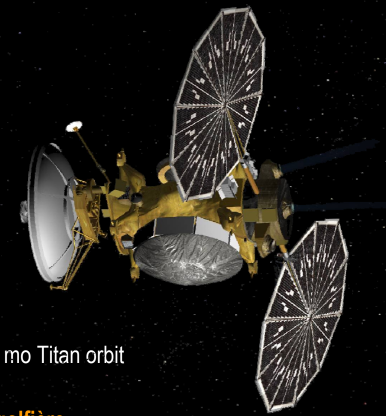
Lake Lander Planning Payload	
TLCA	Titan Lander Chemical Analyzer (GCMS)
TiPI	Titan Probe Imager + Lamp
ASI/MET-TEEP	Atmospheric Structure Instrument/ Meteorological Package + Titan Electric Environment Package
SPP	Surface Properties Package + Acoustic Sensor Package with Magnetometer
LRST	Radio Science using spacecraft/lander telecom system



Mission & Spacecraft Overview

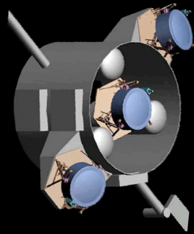
NASA Orbiter with ESA *in situ* elements

- Orbiter + Solar Electric Propulsion (SEP)
- Lake Lander and Montgolfière Balloon
- NASA provided launch vehicle and Radioisotope Power System



Mission Design

- 2020 gravity assist SEP trajectory
- 9 years to Saturn arrival
- SEP stage released ~5 yr after launch
- Montgolfière released on 1st Titan flyby, Lander on 2nd Titan flyby
- ~4 year prime mission: 2 yr Saturn tour, 2 mo Titan aerosampling, 20 mo Titan orbit



Orbiter

- 3-axis stabilized spacecraft
- 4 m High Gain Antenna with 35 W Ka-band amplifier gives high data downlink
- 5 Advanced Stirling Radioisotope Generators (4 baselined, 1 spare) provide 540 W at end of mission (Design also compatible with MMRTG RPS)
- 165 kg instrument payload allocation
- Orbiter dry mass 1613 kg (includes 35% system margin)
- Provides accommodation for two *in situ* elements (833 kg total allocation)
- SEP stage included for inner solar system thrusting
  - 3 NEXT ion thrusters
  - Two 7.5 kW Orion CEV-derived Ultraflex solar arrays
- Total launch mass 6203 kg on Atlas V 551

Montgolfière

- Buoyancy provided by US-supplied Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) (~1700 W thermal)
- 10.5 m diameter envelope
- 10 km nominal cruise altitude
- 6 mo nominal mission length
- Up to 600 kg launch mass including aeroshell
- Telecom relay through orbiter via 0.5 m HGA

Lander

- Lander targeted for northern mare
- Battery operated
- 9 hour nominal mission duration
- 190 kg launch mass including aeroshell
- Telecom relay through orbiter via X-band omni antenna

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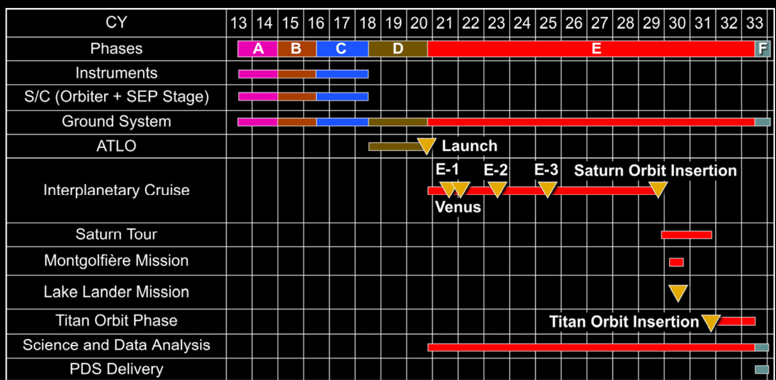
Cost & Schedule

TSSM offers a low-risk mission, employing flight-proven designs for spacecraft, instruments, and ground system.

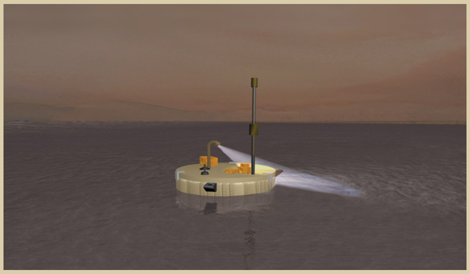
Mission safety is enhanced for TSSM through the implementation of a fully funded risk management and mission assurance program, and through the application of lessons learned from Cassini-Huygens and other recent deep space missions. Ample reserves for all systems reduce cost, schedule risk and help ensure mission success.

Total mission costs of TSSM are estimated to be respectively $3.7B (RY) or $2.5B (FY07) for NASA and up to €650 M (FY07) for provision of the *in situ* elements. The mission will benefit from substantial investments from CNES for the development and provision of the montgolfière. European instrumentation will be provided through national funding.



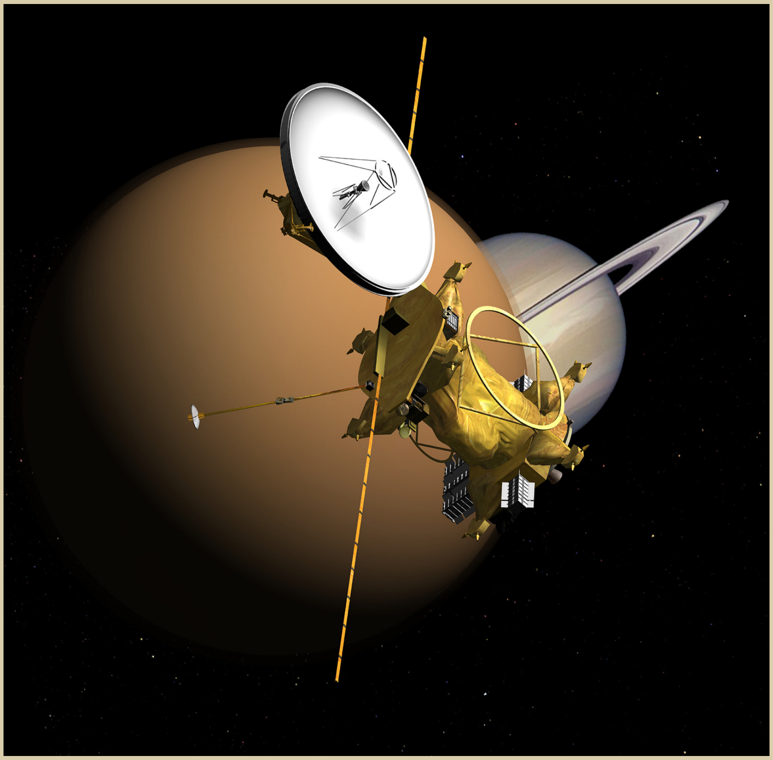
Foreword

A parachute descent—like that of the Huygens probe in 2005—is happening again, but this time in the Saturn-cast twilight of winter in Titan's northern reaches. With a pop, the parachute is released. A few hours later, a muffled splash signals the beginning of the first floating exploration of an extraterrestrial sea—this one not of water but of liquid hydrocarbons.



Thousands of kilometers away, a hot air balloon (a montgolfière) cruises 10 kilometers above sunnier terrain, imaging vistas of dunes, river channels, mountains and valleys carved in water ice, and probing the subsurface for vast quantities of "missing" methane and ethane that might be hidden within a porous icy crust. The data are relayed to a Titan orbiter equipped to unveil Titan's mysteries with instruments for imaging, radar profiling, and atmospheric sampling, much more powerful and more complete than done by Cassini.

This spacecraft, preparing to enter a circular orbit around Saturn's cloud-shrouded giant moon, has just completed a series of flybys of Enceladus, a tiny but active world with plumes composed of water and organics being blown outward from its interior into space. As it flew by Enceladus, the Titan orbiter analyzed these plumes directly. Titan and Enceladus could hardly seem more different, and yet they are linked by their origin in the Saturn system, by a magnetosphere that sweeps up mass and delivers energy, and by the possibility that one or both worlds harbor life.



It is the goal of the NASA/ESA Titan Saturn System Mission (TSSM) to explore and investigate these exotic and inviting worlds, to understand their natures and assess the possibilities of habitability in this system so distant from our home world.

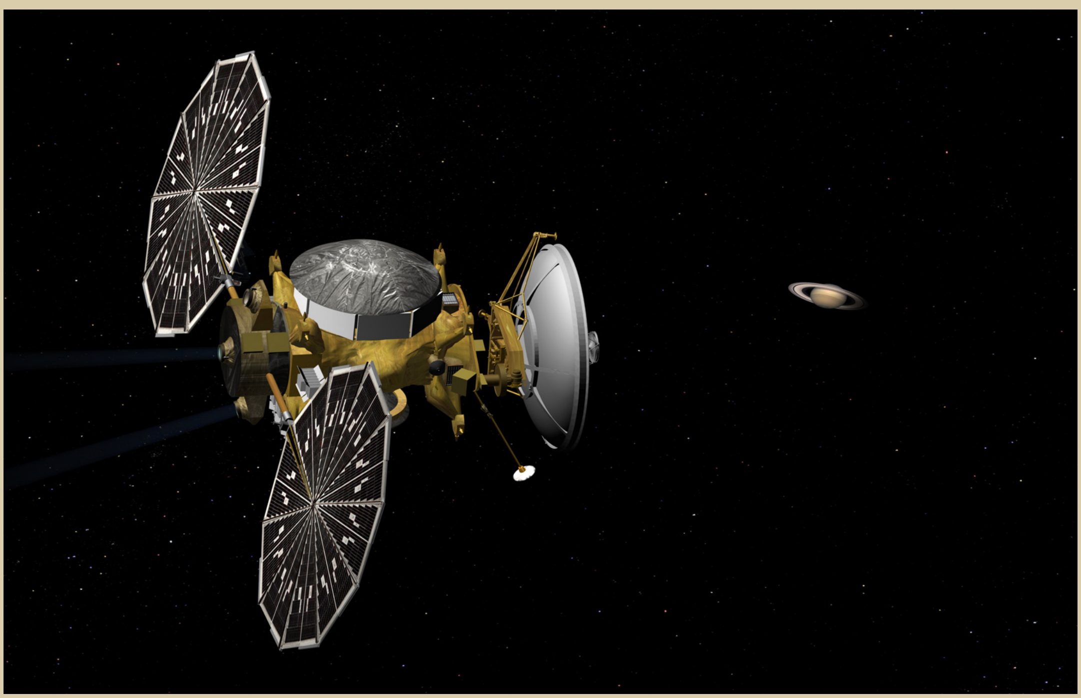
Orbiting, landing, and ballooning is a new and exciting approach to exploring Titan. The TSSM mission architecture provides the optimal balance between science, risk, and cost using three guiding principles:

Achieve "Decadal" science well beyond the high bar set by Cassini-Huygens.
The TSSM orbiter, lander, and balloon have been configured with instruments and an operational concept that go well beyond the capabilities of Cassini-Huygens, thus ensuring dramatic remote observations and *in situ* scientific discoveries.

Build upon lessons learned from successful design and operational experience.
With Huygens, ESA demonstrated that it can design and land probes on Titan, and with Cassini, NASA has demonstrated that it can accurately deliver *in situ* spacecraft and implement long-lived orbiters at Saturn. Long-life design rules and extensive operational experience in the Saturn system have been applied to form the TSSM concept. Lessons learned from Galileo, Cassini, New Horizons, and Mars Reconnaissance Orbiter have been applied to reduce risk and lower cost. Development of the montgolfière by ESA combines prior experience with Earth and planetary balloon systems to enable innovative science and unprecedented mobility for exploring Titan's lower atmosphere, surface, and subsurface.

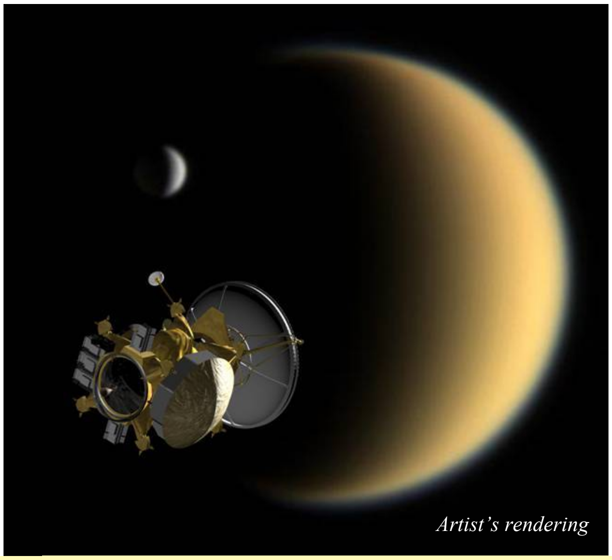
Leverage international collaboration.
TSSM would be a collaborative effort between NASA and ESA that has been designed to provide the best mission possible but at relatively low costs to NASA and to ESA. This NASA/ESA partnership uses international resources to maximize science return, reduce risk, and ensure technical readiness.

TSSM will revolutionize our understanding of the Titan system well beyond what Cassini-Huygens has done and will accomplish during its extended mission.



1.0 EXECUTIVE SUMMARY

1.1 Overview



Titan is a high priority for exploration, as recommended by NASA's 2006 Solar System Exploration (SSE) Roadmap (NASA 2006), NASA's 2003 National Research Council (NRC) Decadal Survey (NRC Space Studies Board 2003) and ESA's Cosmic Vision Program Themes. Recent revolutionary Cassini-Huygens discoveries have dramatically escalated interest in Titan as the next scientific target in the outer Solar System. This study demonstrates that an exciting Titan Saturn System Mission (TSSM) that explores two worlds of intense astrobiological interest can be initiated now as a single NASA/ESA collaboration.

The Cassini-Huygens mission has revealed the Earth-like world of Saturn's moon Titan and showed the potential habitability of another moon, Enceladus. As anticipated by the 2003 Decadal Survey, recent Cassini-Huygens discoveries have revolutionized our understanding of the Titan system and its potential for harboring the "ingredients" necessary for life. These discoveries reveal that Titan is very rich in organics, possibly contains a vast subsurface ocean, and has energy sources to drive chemical evolution. The complex interaction between the atmosphere and surface produces lakes, dunes, and seasonal changes that are features that Titan shares with Earth. Cassini's discovery of active geysers on Enceladus revealed a second icy moon in the Saturn system that is synergistic with Titan in understanding planetary evolution and in adding another potential abode in the Saturn system for life as we know it. These discoveries have dramatically escalated the interest in Titan as the next scientific target for an outer Solar System mission.

Although the scope of science possible at Titan covers the entire range of planetary science disciplines, the TSSM team has developed a mission that focuses NASA and ESA resources on the highest priority science questions. Results of this study confirm that a flagship-class mission to Titan (including the Saturn system and Enceladus) can be done at acceptable risk within the specified budgetary constraints and can proceed now.

1.2 Background

NASA and ESA are completing Pre-Phase A concept studies in support of a joint selection process for the next Outer Planet Flagship Mission (OPFM).

The Titan Saturn System Mission (TSSM) study was directed to redesign the 2007 Titan Explorer mission concept to meet new constraints specified under the revised Requirements and Ground Rules document (2008) and Statement of Work (2008), key elements of which are listed below.

- Respond to the 2007 Study independent review board findings.
- Produce a mission concept that optimally balances science, cost, and risk.
- Define a NASA/ESA Baseline and Floor mission that includes a NASA-provided Titan orbiter that does not utilize aerocapture. The orbiter shall have the capability of delivering and providing relay communications for multiple Titan in situ elements that would be provided by ESA as part of a collaborative program.
- Define a NASA-only mission and Floor mission that can be implemented by NASA in the event ESA does not participate.
- Include Saturn system and Enceladus as Level 1 science requirements to the extent they inform us about Titan.
- Include minimum of 33% reserves/margins in all areas.

- Use a launch date of 2020 for schedule and cost purposes. Alternative launch dates from 2018 through 2022 should be identified.

This study and its predecessors are intended to support a joint NASA-ESA down-select to a single OPFM expected in February 2009.

1.3 Study Approach

TSSM builds upon the results of more than a decade of previous studies as well as thorough science assessment, rigorous systems engineering, and experience gained from the Cassini-Huygens mission to develop a high fidelity concept in support of the NASA/ESA OPFM down-selection process.

An international science and technical team was formed with the goal to develop a focused, cost-effective TSSM (**Figure 1.3-1**). NASA and ESA formed a Joint Science Definition Team (JSDT) with 16 US and 15 European members. It was led by a NASA-appointed co-chair (from the University of Arizona, UA) and an ESA-appointed co-chair (from ESA/ESTEC) that established science objectives and participated in the design of the mission. JPL and ESA jointly formed the technical team with members from JPL, APL, NASA Glenn, ESA/ESTEC, ESA/ESOC, and CNES. It designed the mission and its elements. The JSDT and technical team worked as an integrated unit to define a mission that fully responds to the Statement of Work and Ground Rules for this study. This was achieved by establishing science goals and objectives that derive directly from guiding documents and then tracing these forward to define a planning payload and technical requirements on the mission as described in §2.0 and §4.1.1. These provided the basis for the team to develop a concept that balances cost and risk and achieves the science goals established by the JSDT as described in §2.0.

The Baseline Mission concept developed by the study team includes a NASA orbiter with Solar Electric Propulsion (SEP) stage and ESA provided lander and montgolfière balloon. The floor for this NASA-ESA mission preserves all flight elements except the SEP stage with the impact of taking as much as 1.5 years longer to reach Saturn.

1.4 Science Overview

Titan, a rich, diverse body offering the potential for extraordinary scientific return, is emerging as the compelling choice for the next Outer Planet Flagship Mission.

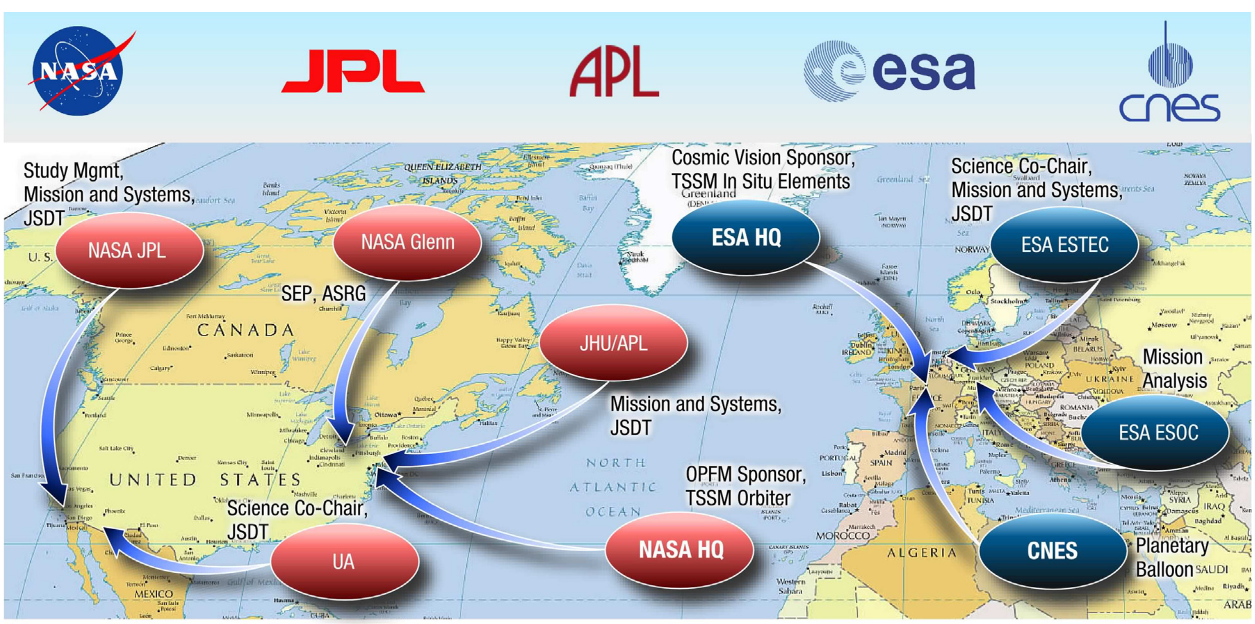


Figure 1.3-1. NASA/ESA geographically diverse team operates as a seamless integrated unit incorporating lessons learned from the Cassini-Huygens model.

Titan, a complex, Earth-like moon with organics, shares features both with other large icy satellites and the terrestrial planets. It is subjected to tidal stresses, and its surface has been modified tectonically to form mountains. It is likely that cryovolcanism exists where liquid water, perhaps in concert with ammonia and carbon dioxide, makes its way to the surface from the interior. Cassini revealed that Titan has the largest accessible inventory of organic material in the solar system aside from Earth, and its active hydrological cycle is analogous to that of Earth, but with methane replacing water. Titan's clouds, rain, flash floods, and greenhouse and anti-greenhouse effects might provide important lessons for Earth's long-term climate evolution. Albeit with dramatically different chemistry, Titan's landscape appears remarkably Earth-like, featuring dunes, fluvial channels, and mountain ridges, as well as polar lakes filled with liquid hydrocarbons. Titan's dense atmosphere is mostly nitrogen—like Earth's—and varies seasonally in temperature, dynamical behavior, and composition, including a winter polar structure analogous to Earth's ozone hole. Finally, although Titan is similar to Earth in many ways, its atmosphere is unique in the solar system, experiencing strong dynamical forcing by gravitational tides (a trait Titan may share with many extrasolar planets). A mission launched in the 2018–2022 timeframe provides a unique opportunity to measure a seasonal phase complementary to that observed by Voyager and by Cassini, including its extended missions.

Recent discoveries of the complex interactions of Titan's atmosphere with the surface, interior, and space environment demand focused and enduring observation over a range of temporal and spatial scales. The TSSM two-year orbital mission at Titan would sample the diverse and dynamic conditions in the ionosphere where complex organic chemistry begins, observe seasonal changes in the atmosphere, and make global near-infrared and radar altimetric maps of the surface. This study of Titan from orbit with better instruments has the potential of achieving a *2–3 order-of-magnitude* increase in Titan science return over that of the Cassini mission.

Chemical processes begin in Titan's upper atmosphere and could be extensively sampled by an orbiting spacecraft alone. However, there is substantial additional benefit of extending the measurements to Titan's lower atmosphere and the surface. Titan's surface may replicate key steps toward the synthesis of prebiotic molecules that may have been present on the early Earth as precursors to life. *In situ* chemical analysis, both in the atmosphere and on the surface, would enable the assessment of the kinds of chemical species that are present on the surface and of how far such putative reactions have advanced. The rich inventory of complex organic molecules that are known or suspected to be present at the surface makes new astrobiological insights inevitable. *In situ* elements also enable powerful techniques such as subsurface sounding to be applied to exploring Titan's interior structure. Understanding the forces that shape Titan's diverse landscape benefits from de-

Figure 1.4-1. *The TSSM orbiter will have multiple opportunities to sample Enceladus' plumes.*

tailed investigations of various terrain types at different locations, a demanding requirement anywhere else, but one that is uniquely straightforward at Titan using a montgolfière hot-air balloon. TSSM's montgolfière can circumnavigate Titan carried by winds, exploring with high resolution cameras and subsurface-probing radar. The combination of orbiting and *in situ* elements is a powerful and, for Titan, unprecedented opportunity for synergistic investigations—synthesis of data from these carefully selected instrumentation suites is the path to understanding this profoundly complex body.

En route to Titan, opportunities exist to significantly extend our understanding of Saturn's magnetosphere. Furthermore, the tour through the Saturn system will take the orbiter through the plumes of Enceladus (**Figure 1.4-1**). Using more capable instrumentation not available on the Cassini spacecraft, these investigations would not only inform us about these fascinating parts of the Saturn system, but would help us address important questions about Titan as well.

The TSSM Science Goals as shown in **Table 1.4-1** respond directly to NASA's science objectives, ESA's Cosmic Vision themes, and science questions raised by the extraordinary discoveries by Cassini-Huygens. TSSM science would embrace geology, meteorology, chemistry, dynamics, geophysics, space physics, hydrology, and a host of other disciplines. Thus, it would engage a wider community than for virtually any other target in the outer Solar System. Clearly, Titan, a rich, diverse body offering the promise of extraordinary scientific return, is emerging as the compelling choice for the next NASA Flagship mission.

Table 1.4-1. *TSSM science goals.*

Goal	Summary
Goal A: Titan: an Earthlike System	How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?
Goal B: Titan's Organic Inventory	To what level of complexity has prebiotic chemistry evolved in the Titan system?
Goal C: Enceladus and Saturn's magnetosphere	What can be learned from Enceladus and from Saturn's magnetosphere about the origin and evolution of Titan?

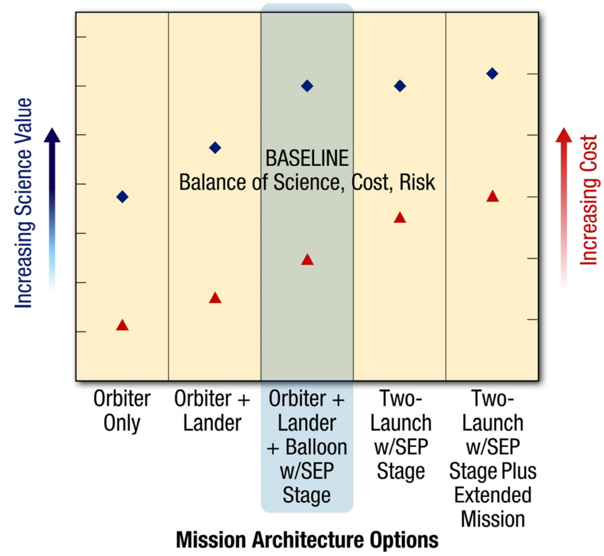


Figure 1.5-1. *TSSM's Baseline architecture maximizes science return to investment ratio within NASA and ESA resources, at risk comparable to Cassini-Huygens.*

1.5 Mission Architecture Assessment

A robust architecture has been developed that enables NASA/ESA or NASA-only mission options that respond comprehensively to the science requirements.

Many different mission architectures and trades were explored. Various combinations of orbiter and *in situ* elements, propulsion elements, single-launch versus multiple-launch scenarios and delivered mass versus trip time performance were assessed. Per the study ground rules, aerocapture concepts were not pursued as part of this study but can be found in the 2007 Titan Explorer study report.

The TSSM Baseline mission was chosen from a comprehensive assessment of alternative concepts and was found to be the optimal balance between science, cost, and risk. Results shown in **Figure 1.5-1** indicate that the combination of orbiter, solar electric propulsion, lander, and montgolfière provides the highest science value per unit of currency invested.

This Baseline mission architecture provides descope options for both NASA and ESA to a scientifically attractive NASA/ESA Floor mission (as shown in **Figure 1.5-2** and de-

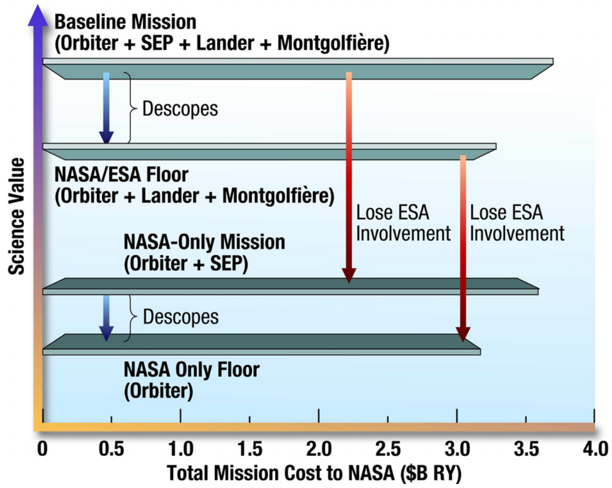


Figure 1.5-2. *NASA/ESA and NASA-only mission architectures include robust descopes while remaining above the science floor.*

scribed in §3.3.1.2), yielding a very robust project implementation plan. The Baseline is comprised of a NASA orbiter with SEP stage and ESA-provided lander and montgolfière hot air balloon. The floor for this NASA/ESA mission would not include the SEP stage, in addition to other potential descopes (§4.11.7.8), and would result in a 1.5-year longer interplanetary trajectory. The impact to science is limited to later return of science data. The impact to the mission is reduced flexibility.

In the event of an ESA decision not to participate, a NASA-only mission could proceed. If this decision is made late in the process an exciting orbiter-only mission would be feasible that fully meets the Level 1 science requirements. However, if the decision occurred during or prior to Phase A there would be the possibility of a mission with US provided *in situ* elements (and/or possibly other international contributions). Investigating non-ESA provided *in situ* elements was beyond the scope of this study and therefore the orbiter-only option was assessed. The orbiter-only architecture described in this report preserves Titan, Saturn system, and Enceladus Level 1 science but gives up montgolfière and lander measurements. The impact to science of the fully descoped NASA-only orbiter mission is limited to later return of science data. The impact to the mission is reduced flexibility.

An orbiter-only mission with the instrument complement described here provides a qualitatively different and quantitatively more powerful data set about Titan than did Cassini-Huygens, and will fundamentally revolutionize our understanding of Titan. It will do likewise for Enceladus. The orbiter-only mission has been judged by the JSDT to be well worth the price of a Flagship-class mission.

Transition to a viable NASA-only mission can occur at any time and at any point in any descope sequence from the Baseline mission to the NASA/ESA Floor mission. An important characteristic of this structure is that if an ESA decision not to participate occurred, even up to launch, there are clear transition pathways from the NASA/ESA mission to a viable NASA-only mission.

1.6 Mission Implementation

TSSM implementation options include orbiter and in situ elements that build upon and apply the design, operational experience and lessons learned from Cassini-Huygens, Galileo, Mars Orbiter, New Horizons, Dawn, MESSENGER, Beagle-2 and Exomars missions.

The flight elements shown in **Figure 1.6-1** would be launched on an Atlas V 551 launch vehicle in 2020 using a gravity-assist SEP trajectory to achieve a trip time of 9 years to Saturn. Following Saturn orbit insertion, the orbiter would conduct a Saturn system tour, including 7 close Enceladus flybys and 16 Titan flybys. This phase will allow excellent opportunities to observe Saturn, multiple icy moons and the complex interaction between Titan and Saturn's magnetosphere. The montgolfière would be released on the first Titan flyby, after Saturn orbit insertion, and would use an X-band relay link with the orbiter for communications. The lander would be released on the second Titan flyby and communicate with the orbiter during the flyby only. This 24-month period will also mark the mission phase when all of the Titan *in situ* data is relayed back to Earth. Following its tour of the Saturn system, the orbiter would enter into a highly elliptical Titan orbit to conduct a two-month concurrent Aerosampling and Aerobraking Phase in Titan's atmosphere, sampling altitudes as low as 600 km. The orbiter would

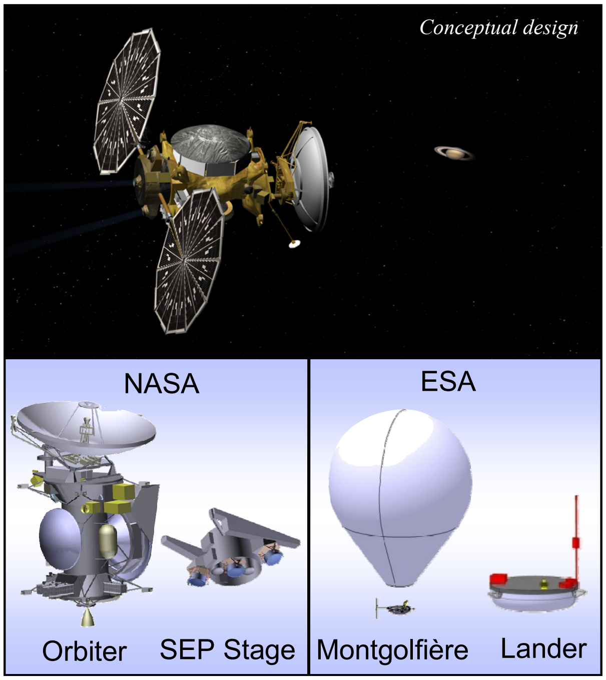


Figure 1.6-1. *Baseline mission concept includes coordinated orbital observation and in situ elements.*

then execute a final periapsis raise burn to achieve a 1500-km circular, 85° polar-mapping orbit. This Circular Orbit Phase will last 20 months.

On completion of the mission, a Decommissioning and Disposal Phase would be initiated by performing a moderate sized maneuver that begins the orbit decay. Small maneuvers during the decay will target the final impact site to ensure planetary protection requirements are met.

The orbiter concept has mass allocations of 165 kg for its remote sensing instruments and 830 kg for ESA-provided *in situ* elements. Payload and operational scenarios were developed with the JSDT to meet the prioritized science objectives. Flight and ground systems are sized to provide the data volumes necessary to return measurement data from the orbiter and *in situ* elements.

The integrated JSDT has defined a model/planning payload for the purposes of conducting this study. Instrumentation for the orbiter, lake lander, and montgolfière elements were configured in an optimal way to collaboratively achieve the mission science goals. It is anticipated that NASA and ESA would issue coordinated announcements of opportunity (AO) for the mission instrumentation, respectively for the orbiter and for the *in situ* elements. It is anticipated that instruments related to each of the mission elements would be open for competition throughout the international community as this was the case for Cassini-Huygens.

TSSM benefits from proven experience, proven Flight Systems, existing launch capabilities, lessons learned and well-understood trajectory options. The design relies on traditional chemical propulsion (similar to Cassini and Galileo), proven solar electric propulsion, a power source consisting of five Advanced Stirling Radioisotope Generators (ASRGs) and a robust data relay and downlink system. The concept is also fully compatible with Multi-mission Radioisotope Thermoelectric Generators (MMRTGs). **Table 1.6-1** lists major char-

Table 1.6-1. *Key mission characteristics of the TSSM Baseline mission concept.*

Architecture	Orbiter with *in situ* elements
Launch vehicle	Atlas V 551
Launch date	9/2020
Trajectory	Earth-Venus-Earth-Earth gravity assist
Flight time to Saturn	9 years
Saturn System Tour Phase	24 months
Number of close Enceladus encounters during the Saturn Tour	7
Number of Titan encounters during the Saturn Tour	16
Titan Aerosampling Phase	2 months
Titan Orbital Phase	20 months
Radiation Design Point*	<15 krads
Science Instruments, mass allocation	
Orbiter	6 plus radio science; 165 kg
Montgolfiére	7 plus radio science; ~25 kg
Lake Lander	5 plus radio science; ~32 kg
Average data volume return from Titan orbit	5.4 Gb/Earth day (compressed)
Cumulative data volume	
Orbiter	>4.9 Tb
Montgolfiére	>300 Gb – 1.3 Tb
Lake Lander	>500 Mb – 3.4 Gb

*Behind 100 mils of Al, RDF of 1

acteristics of the Baseline mission. NASA will decide which RPS would be used.

The TSSM concept meets or exceeds reserves and margins prescribed in the study ground rules that exceed JPL's Flight Project Practices and Design Principles developed and used successfully over the past several decades. Design life of the flight system is based on design rules and techniques manifestly demonstrated by Voyager, Galileo, and Cassini during their long-life missions. Environmental risk factors are minimal and well-understood.

The same organizations that partnered on Cassini-Huygens have partnered to bring their experience to carry out TSSM:

- JPL has built and is currently operating the Cassini orbiter at Saturn.
- JPL is the only organization to have delivered probes to the outer planets.
- JPL and APL are the only organizations to have sent RPSs to the outer planets.
- ESA (through CNES) has an active terrestrial ballooning program and has previously worked on balloons for both Mars and Venus.
- ESA is the only organization to have landed a probe (Huygens) on Titan.

1.7 Cost, Schedule, and Risk

The TSSM Baseline concept provides a comprehensive response to science objectives that leverages NASA and ESA resources and reduces risk to ensure technical readiness.

As shown in **Figure 1.5-1**, NASA/ESA and NASA-only options have been defined with associated descope paths.

The total cost to NASA (rounded up) is estimated to be \$3.7B in real year dollars (RY) for the NASA/ESA Baseline mission and \$3.3B (RY) for the NASA/ESA Floor mission. This cost to NASA does not include ESA's costs. The costs to ESA are commensurate with the budget envelope for an L-class mission of the Cosmic Vision 2015–2025 program (650M€ Cost-at-Completion). These ESA costs do not include the development and delivery of the balloon envelope, which will be provided by CNES. Furthermore the provision of science instruments is expected from European national funding, and is therefore also not included in ESA's costs. Clearly this collaborative partnership provides a very significant science-to-cost ratio benefit to both NASA and ESA. In the event that ESA makes the decision not to participate, the cost of a NASA-only mission is estimated to be \$3.6B (RY) and the fully descoped NASA-only Floor mission is estimated to cost \$3.2B (RY).

Budget reserves for these costs were established by comparing a top down architectural assessment of risk with a bottoms-up WBS assessment based upon perceived risk. Reserves estimates from each of these two methods were triangulated with the reserves floor of 33% as called out by the Ground Rules. The larger of the three values was used by the project. As determined from the process described above, the TSSM budget reserves are calculated as:

- Phase A = 10%
- Phase B through D = at 35% per Bottoms Up analysis. The Cost Risk Subfactors analysis yielded a 34% estimate. Further details are discussed in Appendix D.
- Phase E = 15%

The reserves base is the current best estimate cost including RPS but excludes DSN Aperture, Launch System, and EPO.

The TSSM project implementation schedule is based on experience from prior Flagship missions and the unique aspects of this mission. It includes milestones and funded schedule margins consistent with NASA directive NPR 7120.5D and JPL Flight Project Practices. This schedule is driven primarily by long lead procurements, an extensive Verification and Validation (V&V) program, and mission trajectory considerations. Coordination with ESA during development and integration of the *in situ* elements is planned. A timeline for the mission with phase durations, key decision points, and operational modes is shown in **Figure 1.7-1**. The current schedule is based on a 2020 launch as directed in the ground rules for this effort. If a 2018 launch opportunity is preferred, the schedule could be adjusted for the two year advance. Later dates are easily accommodated as well.

An ESA baseline schedule was derived during the assessment study of the ESA provided *in situ* elements and it is confirmed as being compatible with a 2020 launch. Earlier launch dates are also possible.

While the science resulting from TSSM is a giant leap beyond Cassini-Huygens, the development risk for the Baseline TSSM is comparable to that for Cassini-Huygens. Long-lead items such as radioisotope power systems (RPS), propulsion systems, and structure are planned to be initiated early in the development process to ensure on-time availability for integration. Because the NASA orbiter and ESA *in situ* elements build upon Cassini-Huygens, MRO, MESSENGER, Dawn, New Horizons, Beagle-2 and Exomars experience and lessons learned, the technical development, and cost risks are well understood.

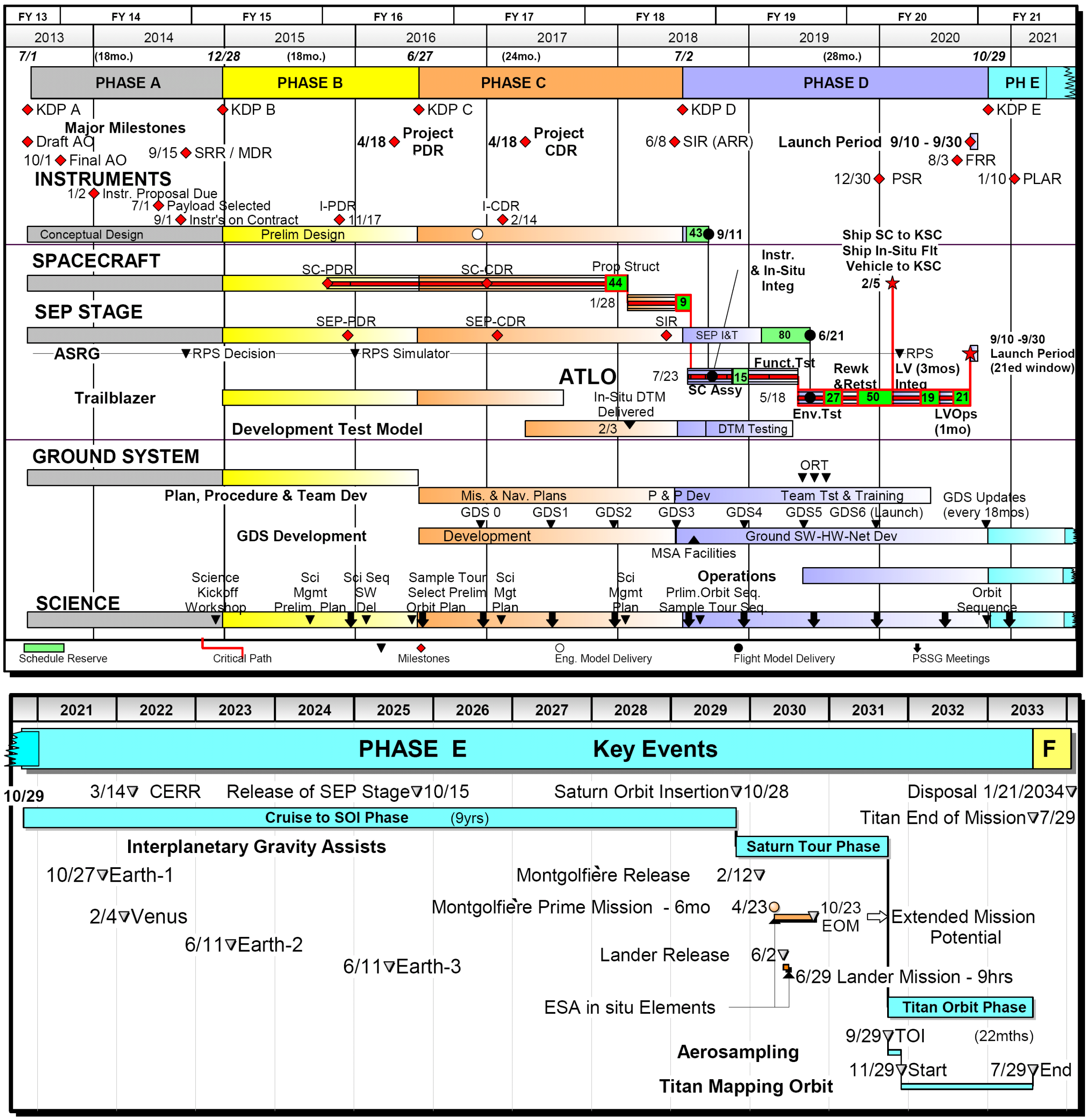


Figure 1.7-1. Top-level Baseline mission timeline.

1.8 Summary and Conclusions

Important science questions are now well established for Titan and the time is right to initiate a dedicated robust mission to answer them. TSSM would provide unequalled value by exploring two worlds of intense astrobiological interest (Titan AND Enceladus) as a single NASA/ESA collaboration. The excitement can continue!

A mission to study Titan in depth is a high priority for exploration, as stated by the 2003 NRC Decadal Survey large satellites panel.

> *Europa and Titan stand out as the highest-priority targets….It cannot now be predicted whether Europa or Titan will ultimately prove to be the most promising satellite for long-term exploration. However, Cassini-Huygens will surely revolutionize our understanding of Titan…*

Since the 2003 Decadal Survey, Cassini-Huygens discoveries have revolutionized our understanding of Titan and its potential for harboring the "ingredients" necessary for life. With these recent discoveries, the high priority of Titan is reinforced (NAI letter, Appendix M).

Remarkably, the picture that has emerged is one in which all the aspects of astrobiological interest are packaged in one body. Titan appears to have an ocean beneath its crust, almost certainly mostly of liquid water. Contact with rock during the early history of Titan, as the body differentiated, would have led to a salty ocean. The ocean would be suffused with organics from Titan's interior and from its surface (delivered by impacts), leaving Titan with a warm, salty, organic-laden ocean. Added to this is a dense atmosphere with active climate and organic chemistry, a surface of hydrocarbon seas and river channels, and a climate system that is more Earth-like in its operation than that of any other place in the solar system.

The Titan Saturn System Mission represents the logical next step in outer planets exploration with a host of features, ready to be implemented now.

- Unequalled exploration of two worlds of intense astrobiological interest (Titan AND Enceladus) in a single NASA/ESA collaboration.
- Major advance beyond Cassini-Huygens in accomplishing Decadal objectives.
- Science engagement over the full range of planetary science disciplines—Geology, Geophysics, Atmospheres, Astrobiology, Chemistry, Magnetospheres—through deployment of new instruments in orbit, in atmospheric flight, and on a large sea, and investigate the plumes of Enceladus in ways that Cassini could not do.
- Built upon a demonstrated capability to design, land, and operate probes on Titan (e.g., ESA Huygens), and Saturn-based orbiters (e.g., NASA Cassini).
- Baseline mission options provide feed forward SEP stage to enable other science missions.
- Leverages synergistic NASA/ESA resources, reduces risk, and ensures technical readiness.
- Ensures programmatic flexibility with frequent launch opportunities.
- Offers NASA-only options in the event ESA decides not to participate.

A unique mission for an extraordinary world, the Titan Saturn System Mission provides a kind of planetary exploration never before attempted by humans and ideally suited to the environment of Titan. This study confirms that the mission is ready to proceed.

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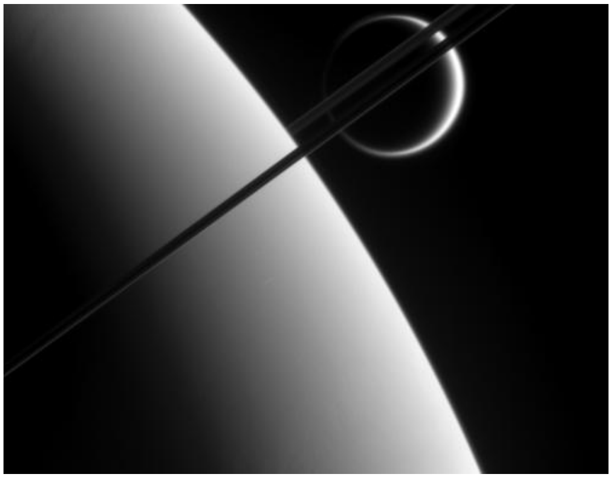
2.0 SCIENCE GOALS AND OBJECTIVES



The Titan Saturn System Mission (TSSM) represents a unique opportunity to execute a comprehensive study of Titan, in a joint NASA/ESA collaboration that combines orbital observations with detailed *in situ* measurements from both aerial and surface platforms. Its goal is Titan, a moon of Saturn larger than the planet Mercury, with a dense atmosphere of nitrogen and methane, surface lakes and seas of liquid hydrocarbons, and a varied landscape that includes dunes, mountains, and liquid-carved valleys. As stipulated by the NASA Statement of Work (2008), the mission addresses both Titan itself and those aspects of the Saturn system that inform us about Titan's origin and evolution. Thus, the same instruments that provide orbital coverage of Titan will be used to gain unique insights into Enceladus during targeted flybys that promise to greatly expand on answers to many of the most intriguing questions raised by Cassini (**Figure 2-1**). Additionally, TSSM will make measurements that shed light on how Saturn's magnetosphere exchanges mass and energy with Titan and in particular feeds ions from other moons such as Enceladus into Titan's atmospheric chemistry. Although not encompassed by the Statement of Work, other targets in the Saturn system—rings, Saturn's atmosphere and icy moons other than Enceladus—can be observed as targets of opportunity during various phases of the mission.

The Baseline mission described in this report involves a full complement of NASA and ESA exploration elements. An orbiter, developed by NASA, would provide accommodation for two ESA-provided Titan *in situ* elements; a montgolfière aerial vehicle that would provide global coverage over a planned six month operating life from a nominal altitude of 10 km, and a short-lived (~9 hr nominal life) lander targeted to a northern hydrocarbon sea. The orbiter would deliver these elements to Titan, and provide data relay during their missions prior to its own insertion into Titan orbit.

The orbiter would provide global coverage of Titan with a rich complement of instruments from a 1500 km circular orbit over a nominal duration of 20 months. Prior to establishing this orbit the orbiter would perform revolutionary science measurements by dipping deep into Titan's atmosphere—hundreds of kilometers deeper than did Cassini—during a two month Aerobraking Phase.

The Titan Saturn System Mission explores, in ways not previously possible, two worlds of intense astrobiological interest (Titan and Enceladus) in a single NASA/ESA collaboration. The mission would investigate Titan across the full range of planetary science disciplines—Geology, Geophysics, Atmospheres, Astrobiology, Chemistry, Magnetospheres—through deployment of new instruments in orbit, in atmospheric flight, and on a large sea, as well as investigate the plumes of Enceladus in ways that Cassini could not do.

While the Baseline NASA/ESA mission is the focus of this report and the following

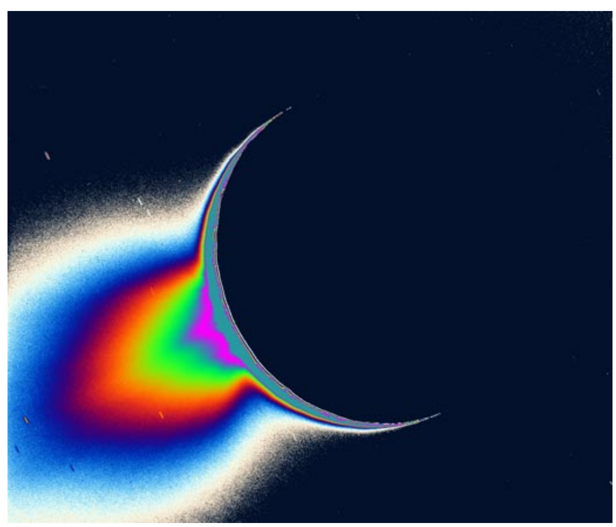


Figure 2-1. *Plumes blast out of the polar region of Enceladus.*

sections, it should be noted that several variations are derived from the baseline and are discussed. They still maintain extraordinary science missions all the way down to the science floor, defined as the NASA orbiter alone. This Floor mission would give up *in situ* measurements from dedicated vehicles, but would retain the full set of orbital science investigations at Titan, as well as *in situ* atmospheric sampling through the Aerobraking Phase, detailed Enceladus science through seven close flybys, and Saturn system science during the Saturn Tour Phase.

2.1 The Relevance and Prominence of Titan Exploration

Saturn's largest moon Titan has been an enigma at every stage of its exploration. For three decades after the hazy atmosphere was discovered from the ground in the 1940s, (Kuiper 1944) debate ensued over whether it was a thin layer of methane or a dense shield of methane and nitrogen. Voyager 1 settled the matter in favor of the latter in 1980, but the details of the atmosphere it determined raised an even more intriguing question about the nature of the hidden surface, and the sources of resupply of methane to the atmosphere. The simplest possibility, that an ocean of methane and its major photochemical product ethane might cover the globe (Lunine et al. 1983), was cast in doubt by Earth-based radar studies (Muhleman et al. 1990), then eliminated by Hubble Space Telescope and adaptive optics imaging in the near-infrared from large ground-based telescopes in the 1990s (West et al. 2005 and references therein). These data, however, did not reveal the complexity of the surface that Cassini-Huygens would uncover beginning in 2004. A hydrological cycle appears to exist in which methane (in concert with ethane in some processes) plays the role on Titan that water plays on Earth (**Figure 2.1-1**). Channels likely carved by liquid methane and/or ethane, lakes and seas of these materials—some rivaling or exceeding North America's Great Lakes in size—vast equatorial dune fields of complex organics made high in the atmosphere and shaped by wind, and intriguing hints of volcanic flows of water across an ice crust suggest a world with a balance of geological and atmospheric processes that are similar to those operating on Earth. Deep underneath Titan's dense atmosphere and active, diverse surface is an interior ocean discovered by Cassini and thought to be largely composed of liquid water.

Cassini-Huygens will leave us with many questions that will require a future mission to answer. These include whether methane is outgassing from the interior or ice crust today, whether the lakes are fed primarily by rain or underground methane-ethane aquifers (more properly, "alkanofers"), how often heavy methane rains come to the equatorial region, whether Titan's surface supported vaster seas of methane in the past, and whether complex self-organizing chemical systems have come and gone in the water volcanism, or even exist in exotic form today in the high latitude lakes. The composition of the surface and the geographic distribution of various organic constituents remain poorly known. Key questions remain about the ages of the surface features, specifically whether cryovolcanism and tectonism are actively ongoing or are relics of a more active past. Ammonia, circumstantially suggested to be present by a variety of different kinds of Cassini-Huygens data, has not been seen. The presence of a magnetic field has yet to be established. The chemistry that drives complex ion formation in the upper atmosphere was unforeseen and is poorly understood. A large altitude range in the atmosphere, from 400–900 km in altitude, remains poorly explored after Cassini. Much remains to be understood about seasonal changes of the atmosphere at all levels, and the long-term escape of constituents to space.

2.1.1 Titan as an Organic-Rich Environment

A key characteristic of Titan is its massive inventory of organic chemicals. The first step in the path toward understanding the role of organics in Titan's atmosphere was the discovery of methane (CH_4) by Kuiper in 1944. Subsequent polarization measurements by Veverka and separately Zellner, both in 1973, indicated the presence of a solid phase component in the atmosphere. These observations were the impetus for the laboratory experiments of Khare and Sagan (1973), which first suggested that methane photolysis could result in solid organic aerosols that Sagan referred to as "tholins" (Sagan and Khare 1979).

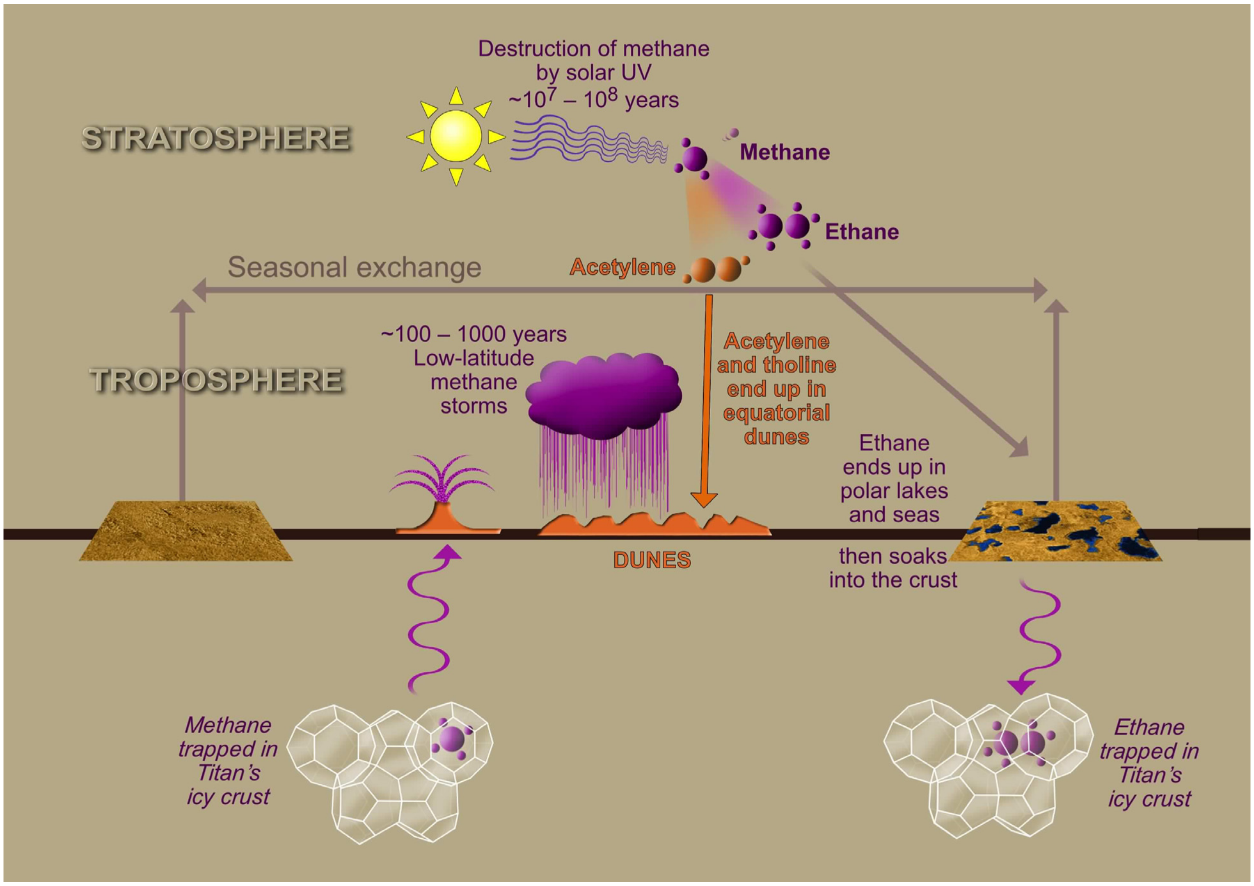


Figure 2.1-1. *A schematic view of the methane cycle on Titan shown with rough timescales for the various processes. The introduction of methane bound in clathrate hydrate into the surface–atmosphere system is shown; methane is either primordial or made in Titan's interior and then outgassed to the surface. It cycles from pole-to-pole, perhaps residing at high latitudes in lakes. Periodically, the equatorial humidity increases to the point that convective storms at low latitudes are possible, carving fluvial features. Photochemistry and charged particle chemistry produce higher hydrocarbons and nitriles, some of which end up in the hydrologic system as ethane, and some as solids that agglomerate to form equatorial dunes. Ethane might be lost to the crust in voids or as clathrate hydrate.*

When Voyager 1 flew past Titan in the early 1980s, it discovered nitrogen to be the primary atmospheric constituent and verified the presence of methane. It detected a host of more complex hydrocarbons and nitriles, only a handful of which had been seen from Earth, that resulted from the photolysis and energetic particle bombardment of the atmosphere. It measured the properties of the thick organic haze that both scattered and absorbed visible and infrared photons, thereby playing an important role in determining the satellite's thermal structure. The laboratory studies carried out on the basis of the Voyager observations thus provided a tholin that was a good model for the Titan haze. Based on this model, it was possible to conclude that the haze on Titan is composed of refractory organics that, once condensed, do not evaporate and are ultimately deposited on the surface with a net production rate of $\sim 10^{-14}$ g cm^{-2} s^{-1} (McKay et al. 2001). Voyager demonstrated that very little oxygen exists in the atmosphere, mainly in the form of CO, with subsequent Earth-based studies providing evidence for water-ice and possibly carbon dioxide on the surface (Lellouch et al. 2003; Griffith et al. 1991; Coustenis et al. 1995).

2.1.2 Titan as a Model for Planetary Climates with Rapid Loss of Volatiles

Far from the Sun, methane plays the active role on Titan that water plays on Earth, acting as a condensable greenhouse gas, forming clouds and rain, and pooling on the surface as lakes. Titan's icy surface is shaped not only by impact craters and tectonics, but also by volcanism in which the lava is liquid water ("cryovolcanism"), by rivers of liquid methane, and by tidally driven winds that shape drifts of aromatic organics into long linear dunes (**Figure 2.2-1**).

And yet this varied landscape, seascape, and weather lacks a methane ocean. Earth's ocean regulates the availability of water for mid-latitude storms and serves as a huge heat sink for climate. Our ocean exists stably on the surface because, at the Earth's distance from the Sun and present solar luminosity, the atmosphere has a profound cold trap at the 15 km altitude level. Over the next one to several billion years, increasing solar brightness will warm our own planet's atmosphere, raise the temperature of the cold trap and allow water to flow into the stratosphere and be broken apart by ultraviolet light. This breakup is irreversible, as the hydrogen will escape, leaving the Earth essentially dry. Residual crustal water will outgas and be resident mostly at the poles, while occasional mid-latitude storms will carve channels amidst a vast equatorial belt of dunes formed by the ocean floor carbonate and silica sediments left behind by the loss of water. Isotopic evidence suggests this happened on Venus billions of years ago, when so much carbon dioxide was available during loss of water to space that the end state of the evolution was a super-greenhouse atmosphere of carbon dioxide and a completely dry surface.

No planet in the solar system is in the state of rapid loss of volatiles today. Titan—a moon rather than a planet—is in such a state. Methane flows into the stratosphere where it is destroyed at a rate limited by the amount of solar UV—not by the amount of methane. Thus, Titan's methane cycle provides a model that can be studied today where the key volatile that provides surface liquids and atmospheric greenhouse opacity is in a state of escape and photo-destruction—an analogue for aspects of the ancient catastrophe on Venus and a plausible fate of our own planet far in the future.

2.2 Science Background

This narrative is provided as a brief introduction to our knowledge of Titan from Cassini-Huygens and thus makes §2.0 self-contained. Readers who are already familiar with the current state of knowledge may wish to skip to §2.3.

2.2.1 Geophysics

Titan's overall density requires it to have roughly equal proportions of rock and ice. The extent of its differentiation (ice from rock, rock from metal) constrains temperatures in the early Saturnian nebula: Titan was almost certainly warm enough to allow differentiation into a rocky core with a water/ice envelope, but whether an iron or iron–sulfur core formed is not known. Thermal evolution models suggest that Titan may have an ice crust between 50 and 150 km thick, lying atop a liquid water ocean a couple of hundred kilometers deep, with some amount (a few to 30%, most likely ~10%) of ammonia dissolved in it, acting as an antifreeze. Beneath lies a layer of high-pressure ice (**Figure 2.2-1**). The presence of ammonia, from which Titan's nitrogen atmosphere was presumably derived, distinguishes Titan's thermal evolution from that of Ganymede and Callisto. Cassini's measurement of a small but significant asynchronicity in Titan's rotation is most straightforwardly interpreted as a result of decoupling the crust from the deeper interior by a liquid layer (Lorenz et al. 2008b).

Both the Cassini Ion and Neutral Mass Spectrometer (INMS) and Huygens Gas Chromatograph Mass Spectrometer (GCMS) measured argon in the atmosphere, with the latter obtaining values for both primordial ^{36}Ar and radiogenic ^{40}Ar. The low value of the former relative to atmosphere N_2 is indirect evidence that Titan acquired its nitrogen originally in the form of ammonia, while the presence of the latter suggests Titan has experienced substantial outgassing over its history (Niemann et al. 2005). A key piece of information that Huygens did not, and Cassini will not, provide is detection and abundance of noble gases other than argon. The presence or

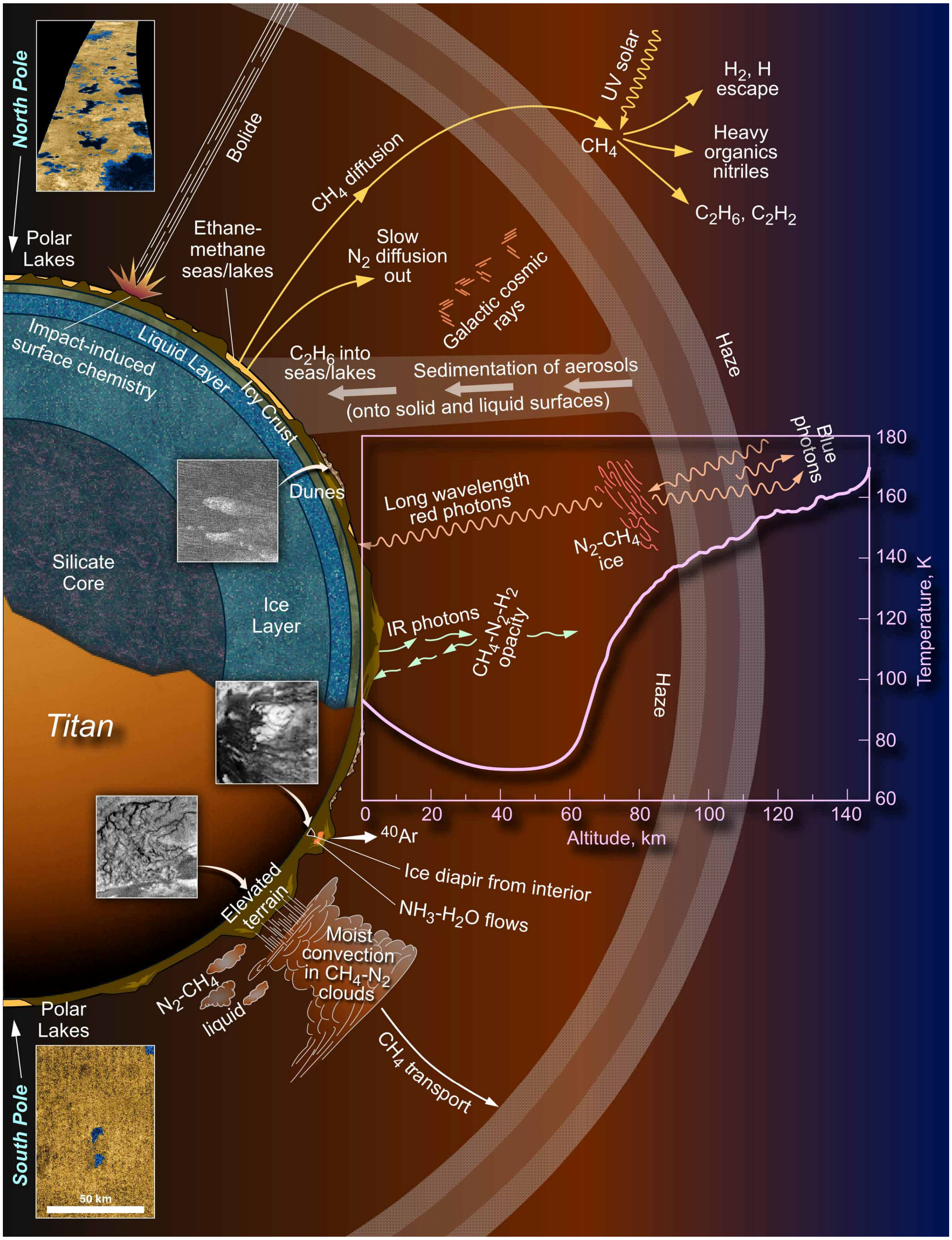


Figure 2.2-1. *Schematic illustration of the connections between Titan's interior, surface, atmosphere, and cosmic environment. Images show lakes at north and south poles, mid-latitude terrains with dunes, and fluvial features carved in the ice crust. Based on an original figure in Lunine (1993) with Cassini VIMS, Radar and Huygens DISR images added. TSSM is designed to quantify these connections. (Features not presented to scale.)*

absence of krypton and xenon is crucial to constraining the origin of methane as either a primordial gas or one manufactured from carbon dioxide deep in Titan's interior (Atreya et al. 2006).

Titan's interior has surely been affected by tidal evolution, since tidal dissipation with the present large (and unforced) eccentricity can be significant. A thermal evolution model by Tobie et al. (2005) suggests that Titan's ice crust was in fact as thin as Europa's (~15 km) for much of Titan's history, and only thickened to ~50 km in the last 500 million years or so (perhaps not coincidentally, the crater retention age determined by Porco et al. 2005 and Lorenz et al. 2007b).

Cassini has made the last of four gravity measurements during the prime mission to determine the gravity coefficients J_2 and C_{22} near apoapsis and periapsis. These coefficients will change appreciably if the interior is fluid enough to respond to the changing tidal potential. Determination of the tidal Love number k_2 with modest precision (~0.1), enough to discriminate between the internal ocean and no-ocean cases, will require additional gravity flybys. Measurements by a Titan orbiter would more quantitatively constrain the internal structure, measuring k_2 more precisely through the lag in tidal response and determining higher-order (up to 5 or 6) gravity coefficients. (Even after only a few days the tracking dataset for the orbiter will surpass the Cassini data.) The gravity coefficients will shed light on whether continental-scale features on Titan such as Xanadu are associated with gravity anomalies.

Titan's rotational dynamics are also a window into its interior. As on Earth, the rotation period of the surface can change over the course of a year as a result of changes in atmospheric angular momentum. On Titan these changes are significant, altering the day length by some hundreds of seconds, leading to many tens of kilometers of displacements if the crust is decoupled from the interior by an ocean, as seems to be the case (Lorenz et al. 2008b). The pole position of Titan also has significance—gravitational torques should cause this to precess (in a Cassini state, the orbit normal and rotational pole precess together, with the obliquity between them dependent on the body's moment of inertia) with a period of around 600 years, perhaps a short enough timescale for differences between a Cassini determination and a follow-on mission to be noticeable. Radar imagery is particularly suited to rotation determination, although with adequate orbital position and attitude knowledge, near-IR sensing may work too.

2.2.2 Titan's Atmosphere

Meteorologically, Titan is an outstanding body for comparative planetology. In some senses it resembles Venus (in being a slowly rotating body with a massive, optically thick atmosphere—conditions that might lead to super-rotating zonal winds). In other respects it may resemble Mars, in having a seasonal cycle forced by an appreciable obliquity (Titan 26°, Mars 25°) and having asymmetric seasons, since their orbits around the sun are eccentric. Titan's southern summer (like that of Mars) is shorter but more intense than the corresponding season in the North. The seasonally changing solar forcing leads to an asymmetric hemisphere-to-hemisphere meridional ('Hadley') circulation, with only a transient epoch of symmetric equator-to-pole Hadley circulation around equinox characteristic of our world. Titan's thermally-direct stratospheric meridional circulation transports organic gases and haze, leading to the seasonal north-south albedo asymmetry in the haze observed by Voyager. The northern hemisphere, observed by Voyager at northern spring equinox in 1980 had more haze and was thus darker at blue wavelengths. This situation had reversed half a Titan year later when the Hubble Space Telescope re-observed Titan. Substantial changes in the haze structure are apparent even after only one or two years (Lorenz et al. 1999).

Titan's upper atmosphere is a region where mass and energy are exchanged with the magnetosphere of Saturn, just as the Earth interacts with the solar wind. However, there are three differences: first, Titan has at best a weak intrinsic magnetic field, or none, and so its ionosphere—the region of charged particles—carries the imprint of Saturn's magnetic field (Bertucci et al. 2008). In this respect Titan is more like Venus than the Earth. Second, Saturn's magnetosphere breathes as the solar wind pushes on it with lesser and greater force so that sometimes Titan is in the solar wind (**Figure 2.2-2**) and sometimes it is not. Finally,

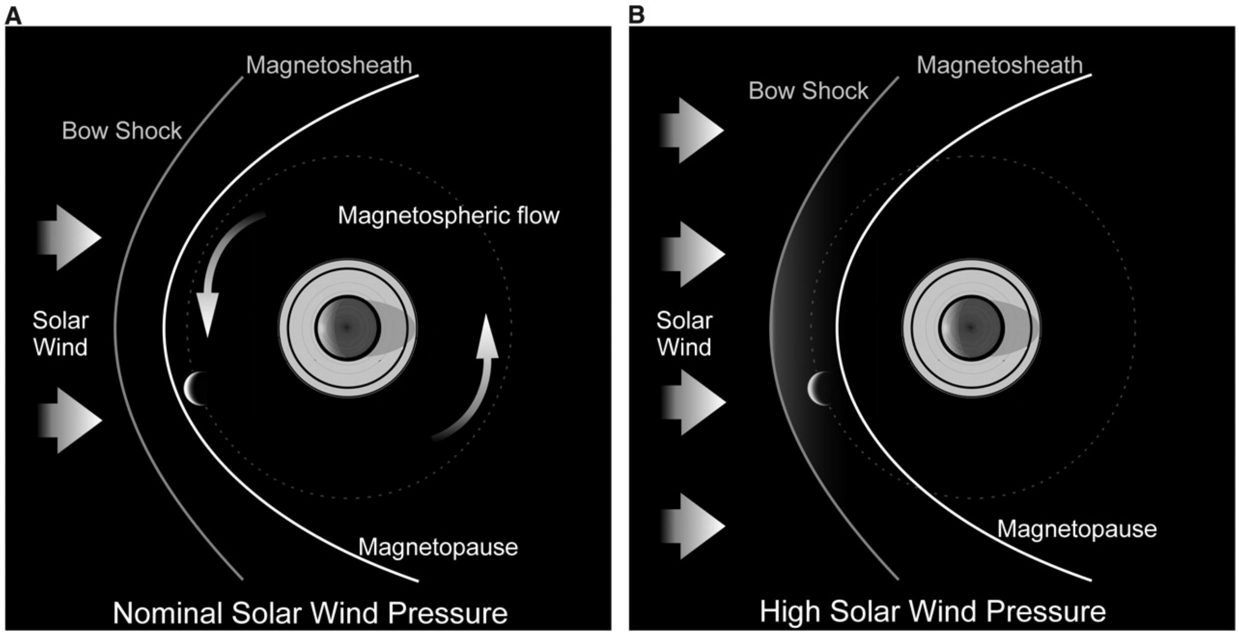


Figure 2.2-2. *Titan's position in the magnetosphere of Saturn. When the solar wind is weak, Titan is inward of the "magnetopause" and carries the imprint of Saturn's magnetic field. When the solar wind is strong Titan is in Saturn's "magnetosheath", and the imprint is erased by the effects of the solar wind encountering a bow shock. (From Bertucci et al. 2008)*

Titan's gravity is much weaker than the Earth's and so loss of molecules is a more important process for Titan than for our home planet.

The two most powerful atmospheric analogies of Titan are those with the Earth. First, most obvious, is the existence of a hydrological cycle involving methane clouds, rain and at least transient rivers. While the possibility of such a cycle had been noted as soon as the proximity of Titan's surface conditions to the methane triple point had been noted in Voyager data, the first evidence of clouds emerged in spectroscopic data (Griffith et al. 1998) and in Hubble Space Telescope (HST) images (Lorenz and Mitton 2002). Subsequent observations showed clouds to be evolving on timescales of only hours, suggesting that precipitation may be occurring, and several years prior to Cassini, large ground-based telescopes with adaptive optics systems showed massive variable cloud systems around the south pole (where it was approaching midsummer) (Brown et al. 2002). Cassini observations soon after its arrival in 2004 showed much detail on these clouds, and showed that the cloud tops ascended at velocities of order a meter per second, comparable with those predicted in models (Porco et al. 2005). These clouds, then, seem fully consistent with cumulus convection like those seen on Earth in desert summer.

From a thermodynamic viewpoint, the relative scarcity of Titan's clouds compared to the Earth can be understood as a consequence of the efficient utilization of a much smaller thermal flux (Lorenz et al. 2005). The geographical distribution, however, is rather different—on Earth rainclouds occur dominantly in the inter-tropical convergence zone, while on Titan models predict that they will broadly speaking track the subsolar latitude (e.g., Mitchell et al. 2006), although the details among models differ (e.g., Rannou et al. 2006).

Titan presents an interesting variation on the Earth's hydrological cycle. While the overall intensity of the cycle is weak, the available solar heating to evaporate surface moisture and drive the cycle is tiny, and not substantially compensated by the lower latent heat of methane compared with water. Thus, instead of the ~100 cm of annual rainfall observed on Earth, Titan must see on average only about 1 cm per (Earth) year (Lorenz 2000). However, Titan's thick atmosphere can hold a prodigious amount of moisture, equiva-

lent to several meters of liquid. Thus, where Titan dumps the moisture out of its atmosphere (which to a crude approximation, is what happens in violent rainstorms, as indicated in models of Titan rainclouds, e.g., Hueso and Sanchez-Lavega 2006; Barth and Rafkin 2007), it would require ~1000 years to recharge the atmosphere. (The corresponding numbers are ~10 cm and a month for the present-day Earth.) A warmer atmosphere can hold more moisture, and may thus see more intense storms separated by longer droughts, a pattern being discerned in the present epoch of global warming. Titan thus has a greenhouse hydrology taken to extremes.

Titan's clouds are not limited to convective cumulus (**Figure 2.2-3**). A pervasive, lingering cloud of ethane particles has been observed over the northern polar regions in the present season (northern late winter), probably related to the down-welling of organic-rich air over the winter pole (Rannou et al. 2006). Additionally, sporadic small cloud streaks have been noted at mid-latitudes with a possibly non-uniform longitude distribution. There is presently debate as to whether these might be associated with the Hadley circulation and/or tides, or whether they are tied to surface features, either as orographic clouds, or clouds triggered by surface venting of methane. Some support for a low-latitude methane supply has been noted in models (much as the Martian climate causes water to migrate to high latitudes) that point out that the low latitudes on Titan should progressively become desiccated in methane (e.g., Rannou et al. 2006), unless replenished by a surface source.

Figure 2.2-3. *Cassini near-infrared image of an ethane cloud capping Titan's north polar region. Red is the longest wavelength (5 µm); blue and green are 2 and 2.7 µm respectively. Courtesy NASA/JPL/U. Arizona.*

Another point of comparison with the Earth is the polar stratosphere. Titan was observed by Voyager to have a UV-dark 'polar hood,' a dark haze cap over the winter pole. This cap was seen in high phase-angle images to stand above the main haze deck, and connect with the detached haze layer. Circulation models (e.g., Rannou et al. 2006) are able to reproduce this behavior. These same latitudes are also known to have both the warmest and coldest parts of the stratosphere, as well as enhancements by factors of ~100 in the abundance of certain nitrile gases. Evidently the upper atmospheric meridional flow converges at the pole and down-welling brings organic-rich air to lower levels. At low altitudes in this feature, low temperatures are found because the region is in winter shadow, and the rich supply of gas and haze provides efficient radiative cooling. In contrast, higher altitudes are illuminated, and also heated adiabatically by the descending air. While connected to the detached haze at high altitude, the region is dynamically isolated by the circumpolar vortex. On Earth, the corresponding circumpolar winds isolate the winter stratosphere from the rest of the atmosphere: the catalytic surfaces of polar stratospheric clouds that form in the winter night cause the destruction of ozone whose concentration becomes locally depleted —the ozone hole (Flasar et al. 2005).

A rich set of chemical, radiative, and dynamical feedbacks is associated with the evolution of the polar hood, with many analogies to the ozone hole on Earth. Cassini may observe the early decay of that in the north, but a subsequent mission will be able to observe the formation of a corresponding feature in the south—HST observations of the decay of the south polar hood (Lorenz et al. 2005) at the same season (2002–2003) show that there are substantial year-to-year changes to observe. An important aspect of studies of these features with a follow-on mission is not only to observe the optical albedo (possible only in illuminated areas) but to observe the coupled temperature, composition, haze and wind

fields, at both poles, in order to disentangle the chain of cause and effect.

The direct analysis of the ionosphere by the INMS instrument during the closest Cassini flybys of Titan shows the presence of many organic species, in spite of the very high altitudes (1100–1300 km) (Waite et al. 2007). Extrapolation of the INMS measurements (limited to mass up to 100 Da) and of Cassini Plasma Spectrometer (CAPS) data, strongly suggests that high-molecular-weight species (up to several 1000 Da) may be present in the ionosphere. These new data—if confirmed—revolutionize understanding of the organic processes occurring in Titan's atmosphere, with a strong implication that ionospheric chemistry plays a role in the formation of complex organic compounds in Titan's environment, which was not envisaged before (Waite et al. 2007). Thus, it appears that Titan is a chemical factory in which the formation of complex positive and negative ions is initiated in the high thermosphere as a consequence of magnetospheric-ionospheric-atmospheric interaction involving solar EUV (Extreme Ultraviolet), UV (Ultraviolet) radiation, energetic ions and electrons. The implications for the prebiotic Earth's atmosphere have yet to be considered in detail but will certainly increase the number and diversity of organic molecular sources on our home planet.

With the current picture of Titan's organic chemistry, the chemical evolution of the main atmospheric constituents—dinitrogen and methane—produces complex refractory organics which accumulate on the surface, together with condensed volatile organic compounds such as HCN and benzene. The second most abundant constituent, methane, is dissociated irreversibly to produce hydrocarbons (e.g., C_2H_2, C_2H_4, C_2H_6 and C_3H_8) and nitriles, (e.g., HCN, HC_3N), from the coupled nitrogen chemistry. The Composite Infrared Spectrometer (CIRS) on board Cassini has detected these organics in Titan's stratosphere and determined their spatial and vertical distributions (Coustenis et al. 2007). Comparisons with previous Voyager and Infrared Space Observatory (ISO) results (Coustenis et al. 2003) have not yet pointed to any significant temporal variations of these species, but the seasons of these measurements were very similar. On the other hand, many of the neutral constituents predicted by models and laboratory measurements and listed on CIRS "shopping list" have failed to turn up (Flasar et al. 2004). The reason could be the geometry or the rareness of the observations, or the detectability limit of the instrument.

A final, and perhaps unexpected, connection may be between Titan and extrasolar planets. Many of the known planets are close enough to their primary to be tidally locked and thus rotate synchronously. However, nonzero eccentricity (as for Titan) may mean that nonetheless there are significant tidal effects. Walterscheid and Schubert (2006) have suggested that tidal forcing may be responsible both for the anomalous and unexpected layer of "negative" wind shear (sharp decrease in the wind during descent) measured by Huygens doppler tracking, and for the distinct haze layers observed in Cassini images of Titan's atmosphere. Thus, Titan may provide insight into models of circulation and opacity structure of extrasolar planets.

2.2.3 Titan's Geology

That the surface of Titan was largely hidden from Voyager's view precluded much thought on its landscape before Cassini arrived at Saturn. The detection of rotational variability in Titan's radar and near-IR albedo in the early 1990s suggested that the surface was not homogenous, as might be expected from a uniform deposition of photochemical debris—something had to be making or keeping bright areas bright and dark areas dark. The variegated surface was revealed with near-IR images by HST in 1994, yielding the first maps (e.g., Smith et al. 1996). However, the poorly resolved patterns of bright and dark gave few clues to these areas' origin, and efforts to interpret the near-IR albedo in the few methane window regions in which the atmosphere is transparent did little more than suggest "dirty ice," with various compositions and amounts of dirt suggested (Coustenis et al. 1995; Negrão et al. 2006).

The first Cassini data (e.g., Porco et al. 2005; Elachi et al. 2005; Sotin et al. 2005) showed that Titan has striking surface features on all scales, the result of a variety of geological processes. The pattern of bright-dark boundaries is reminiscent in places of terrestrial shorelines; a striking and as yet unex-

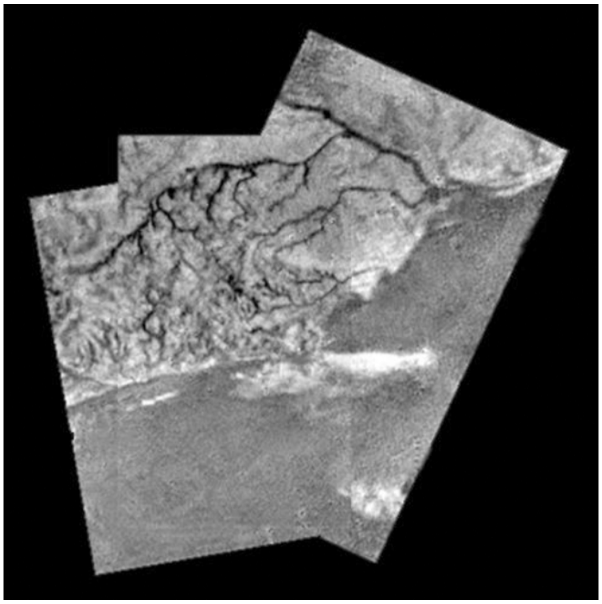


Figure 2.2-4. Fluvial features at the Huygens landing site imaged by the DISR camera. The thickest channels are ~10 m across.

plained feature is that bright–dark contrasts are muted at mid-latitudes.

One remarkable surprise is the relative paucity of impact craters, indicating a relatively young and active surface. Only a handful of impact structures have been named on Titan, ranging from 27 to 440 km in diameter, although some dozens of other likely candidates are identified. Most striking of these are the bright rings such as Guabanito, whose floors are covered in dark sediment (in some places visibly sculpted into dunes). It seems likely that a substantial population of impact structures is buried on Titan, and could be revealed (as in the Martian low-lands) by ground-penetrating radar on a future mission: the present inventory of impact structures, or even that expected by extrapolation into Cassini's extended mission, is too sparse to draw strong conclusions on issues such as leading-trailing asymmetry. Titan's craters appear morphologically different from those on other icy satellites, perhaps due to the role of the atmosphere or subsurface volatiles.

Fluvial modification of the surface was very evident at the Huygens landing site (**Figure 2.2-4**). Not only were steeply incised channels a few kilometers long and ~30 m across observed in the bright highland (which models of sediment transport suggest can be formed in methane rainstorms (Perron et al. 2006), but the knee-height vista from the probe after landing showed rounded cobbles characteristic of tumbling in a low-viscosity fluid. Radar imagery has revealed channels on much larger scales than those seen by Huygens.

Radar-bright channels (probably cobbled streambeds) have been observed at low and mid-latitudes (Lorenz et al. 2007a), while channels incised to depths of several hundred meters are seen elsewhere, and at high latitudes radar-dark, meandering channels are seen that suggest a lower-energy environment where deposition of fine-grained sediment occurs. Whether these larger channels—some of which exceed a kilometer in breadth—and the large-scale flow features near the landing site (Soderblom et al. 2007) would require a different climate regime to be formed remains to be determined—the flow of methane rivers in an unsaturated atmosphere on Titan is very analogous to the problem of ephemeral water flow on Mars—finding out whether the rivers dry out, freeze solid, or drain into an ephemeral sea will depend on presently unknown topographic and meteorological factors.

Beginning in July 2006, a series of flybys of the high northern latitudes of Titan began in which the Cassini orbiter RADAR imaged a variety of very dark features that have been interpreted to be liquid-filled basins—"lakes" (Stofan et al. 2007). The features range in size from less than 10 km^2 to at least 100,000 km^2. They are confined to the region poleward of 55°N. To date some 655 such features have been identified and mapped over seven Titan flybys (Hayes et al. 2008) (**Figure 2.2-5**).

Mapping by Hayes et al. (2008) indicates that above 65°N the dark lakes occupy 15% of the terrain imaged so far. Bright lakes—features that appear similar to the radar-dark lakes but have little or no brightness contrast with their surrounds—tend to replace the dark lakes equatorward of 70°N. An intermediate class of lakes that are somewhat darker than their surroundings, but often show faint features within them, has a latitudinal distribution similar to that of the bright lakes. Neither is seen above 77°N, where the dark lakes predominate. Size selection does not appear to be present in the dark lakes; both very large and very small examples exist. (Coverage by Cassini RADAR in the southern high latitudes

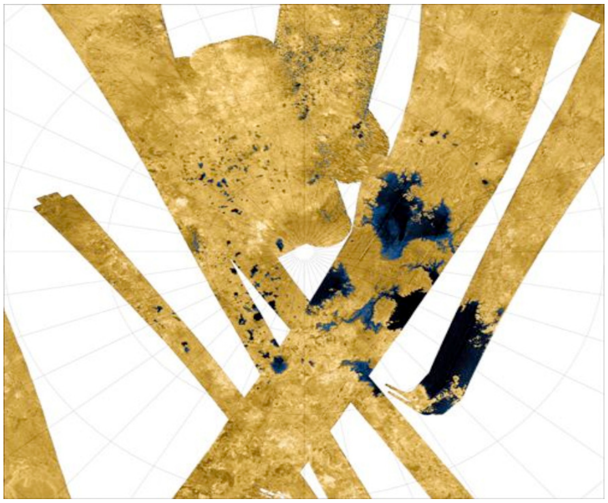


Figure 2.2-5. *Mosaic of the northern hemisphere lakes (dark areas). (NASA/JPL, USGS)*

is very poor; lower resolution imaging and VIMS data show just one large lake over 200 km long).

The hypothesis that the dark lakes are filled with liquid is advanced (Stofan et al. 2007) based on several arguments. First, the dark lakes are in many—but not all places—extremely dark, with reflectivity values below the noise level of the radar system. Since Cassini RADAR never operates in imaging mode at 0^{o}—nadir—incidence, the lack of return indicates reflection off a surface smooth on the scales of the 2.16 cm wavelength of the radar system. A calm liquid surface or smooth solid surface would produce the result. The Huygens landing site was littered with 1–10 cm-scale pebbles and appeared bright to the radar system (Lunine et al. 2008); features as dark as the lakes do not appear at equatorial or mid-latitudes (**Figure 2.2-6**). Evidently, then, the physical surface causing the coherent reflection away from the radar antenna is typical only of the high latitudes and not simple of plains areas devoid of pebbles. Thus, either liquid or a recently frozen, smooth, surface is required.

Second, radiometry measuring the natural thermal emission at the 2.16 cm wavelength of the Cassini RADAR indicates that the dark lakes emit more thermal energy than the surroundings—consistent with hydrocarbons and inconsistent with a smooth surface of water-ice or ammonia-ice (Paganelli et al. 2007), assuming the exposed surrounding crustal material is

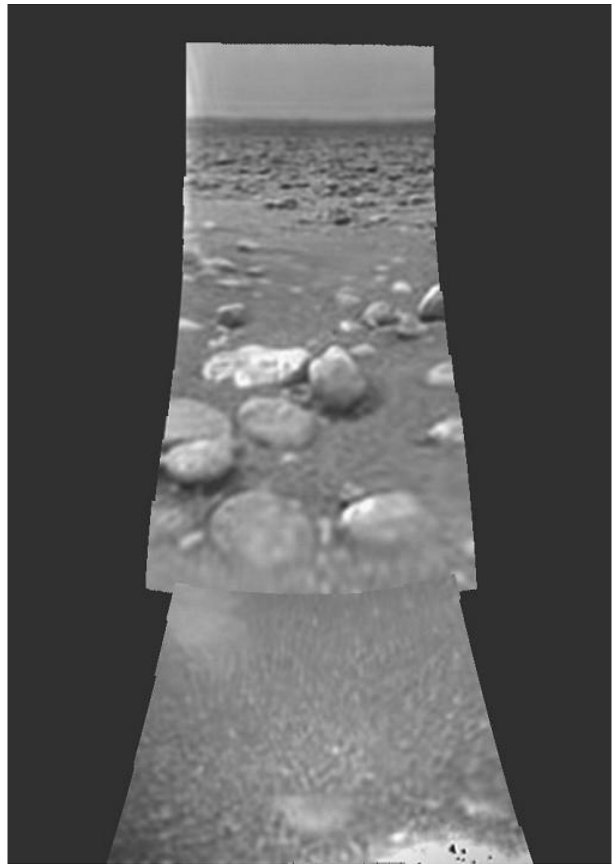


Figure 2.2-6. *Pebbles 10–15 cm in size litter the scene in front of the landed Huygens probe. Made of ice and possibly coated with organics, their rounded form suggests they were tumbled by liquids. Image at the bottom is out of focus because of proximity to the camera. ESA/NASA/JPL/U. Arizona.*

water-ice. Third, the morphology of the boundaries between the largest of the dark lakes and the surroundings resembles a terrain flooded by liquid (**Figure 2.2-7**), with the dark material appearing to flood valleys between hilly terrain and in some cases occupying networks of channels that feed into or out of the lakes Finally, the latitudinal restriction on the occurrence of the dark lakes is consistent with global circulation models that predict precipitation of methane onto both or at least the winter pole (Rannou et al. 2006) together with the decrease in surface temperature poleward (Flasar et al. 2005). Currently the northern pole is approaching spring equinox in an annual cycle that is 29.5 years in length.

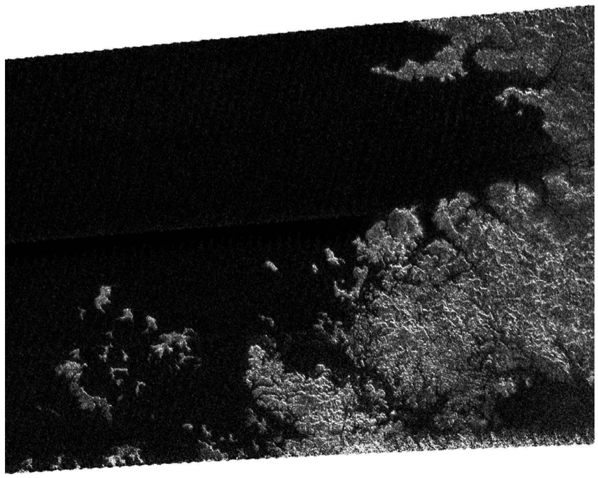


Figure 2.2-7. Cassini radar image of a portion of one of the northern lakes on Titan, showing what appears to be liquid flooding a series of hills and fluvially eroded valleys. This and one other lake are so large that the IAU has denoted them "mare." Image 160 km by 270 km across. (NASA JPL)

All of the above are circumstantial support for the hypothesis that the dark northern hemisphere lakes are filled with liquid, but a definitive demonstration must await detection in the lakes of liquid methane (almost impossible with VIMS) or ethane (difficult but possible). Because the northern reaches are just now experiencing the onset of spring, the sun is low on the horizon above 64°N given Titan's axial tilt of 26° (Stiles et al. 2008). As the season progresses spectra with progressively higher signal-to-noise on the larger lakes (which are large enough that the IAU has designated them "mare," or seas) may test whether either of the two primary liquids in Titan's hydrological cycle is present in the lakes, as was done successfully for ethane in the southern hemisphere feature Ontario Lacus (Brown et al. 2008).

Assuming that the darkest of the northern hemisphere lakes are filled with liquid, it is of interest to know their depths both to understand the total amount of liquid they contain and to understand the underlying geology that has formed them. Both methane and ethane are relatively transparent at 2 cm wavelength, with recent laboratory measurements suggesting absorption lengths (1/e diminution of the signal) of order meters (Paillou et al. 2008). The darkest lakes—which return no radar signal above the instrument noise floor—may therefore have depths that exceed of order 10 m. The lakes that show faint features such as channels may be less than ~10 meters deep allowing the bottom to be seen. The presence of channels suggests these lakes periodically empty and are then subjected to channel formation through flow of methane from the surroundings.

With 22% of Titan's surface now imaged by RADAR, and the lakes covering 2.4% of this, roughly 0.6% of Titan's surface is potentially covered by liquid methane and ethane if the remaining unimaged parts contain no lakes. Mitri et al. (2007) constructed a simple model of evaporation off of high latitude lake surfaces to show that this amount of surface coverage, coupled with advective rates consistent with plausible wind speeds of 0.1–1 m/s (Tomasko et al. 2005), is sufficient to maintain the relative humidity of methane globally on Titan at its present value. However, for an average lake depth of 20 m the reservoir of methane in the lakes is between 1/30 and 1/3 the methane atmospheric inventory (Lorenz et al. 2008a), insufficient to account for the additional methane required to humidify the equatorial atmosphere and permit the convectively-triggered rainstorms that appear to be required to form the dendritic features at the Huygens site (**Figure 2.2-4**). Either the lakes are on average at least an order of magnitude deeper than the minimum inferred from the radar absorption lengths, or additional methane is presence in subterranean porous or fractured media. Alternatively, the dendritic features might be a relic of a wetter recent past.

Even if the average lake depth is only 20 m, the amount of liquid in the lakes is substantial: two orders of magnitude larger than the known oil and gas reserves on the Earth (Lorenz et al. 2008a). Equally impressive is the range of morphologies of the lake and sea features observed to date, from flooded canyonlands to what appear to be liquid-filled calderas.

In contrast to the extensive coverage by RADAR in the northern hemisphere, only one radar pass has been made of the southern hemisphere, revealing just two fairly small lakes. However, ISS images at much lower spatial resolution than the 350–1000 m achievable with the RADAR show a kidney-shaped

dark feature about 200 km in length, Ontario Lacus, that is outside the area of radar coverage and based on VIMS spectra (Brown et al. 2008; Raulin et al. 2008) contains ethane (liquid) and hence is a lake. The observation early in the mission of extensive south polar convective clouds (Porco et al. 2005) that subsequently disappeared suggests that a source of condensed methane exists or existed very recently in that hemisphere; it is possible that additional radar imagery of the southern hemisphere will reveal lakes akin to those in the north but smaller than Ontario Lacus.

Indeed, ISS has documented dozens of such features near the South Pole (McEwen et al. 2005). Another possibility is that, in the intervening time (2.5 years), changes in the distribution of south-polar surface liquids have occurred (Turtle et al. 2008). If such rapid changes do occur, then repeated observations of the polar regions will be important for understanding the methane cycle as well as assessing the total methane inventory. Observing the southern hemisphere at close range during southern springtime to assess whether more lakes are present there then. This will require a mission timed to arrive in a seasonal sense prior to the time of arrival of Cassini-Huygens; Cassini itself will not last until the next southern spring.

Aeolian activity on Titan has proven to be one of the major forces at work at low latitudes. Almost half the terrain within 30° of the equator is covered in dark (presumably organic-rich) streaks or dunes. In a few of the best-imaged regions, these have proven to be dunes many tens of kilometers long and about 150 m high. Almost all appear to be linear (longitudinal) dunes, a type common in the Arabian, Sahara, and Namib deserts on Earth, but very rare on Mars; such dunes form typically in bidirectional wind regimes. A tidal wind origin has been proposed for Titan, but seasonal wind changes may play a role. It is assumed, but has not been shown, that these dunes are presently actively maintained and shaped by the winds; they are certainly young relative to nearby geologic features.

Titan's tectonism is not well understood. A number of very-large-scale linear features are seen optically (Porco et al. 2005), notably the dark dune-filled basins Fensal and Atzlan (known collectively as the "H"). Smaller-scale "virgae" are also seen but are not understood. Radar imagery is not sufficiently widespread to evaluate tectonic patterns, although some linear mountain ranges (Radebaugh et al. 2007) have been detected, several forming a chevron pattern near the equator, and near-IR imagery by Cassini VIMS has also shown long ridges. An outstanding mystery is the nature of the large bright terrain Xanadu and its adjoining counterpart Tsegihi. These areas are distinct optically, and they have unusual radar properties. RADAR imagery shows Xanadu to be extremely rugged, much like the Himalayas on Earth, although the mountain-forming process on Titan has not been robustly identified and may differ from place to place (**Figure 2.2-8**).

Cryovolcanism is a process of particular interest at Titan because of the known astrobiological potential of liquid water erupting onto photochemically produced organics. Radionucleides in Titan's interior, possibly augmented by tidal heating, can provide enough heat to drive a substantial resurfacing rate. Kinetically cryovolcanism is much easier in the Saturnian system, where ammonia can facilitate the rise of water through an ice crust. Ammonia not only depresses the freezing point of water by some 97 K, but also lowers the density of the fluid, thus avoiding the negative buoyancy that likely inhibits cryovolcanism on the Galilean satellites. Several likely cryovolcanic structures have been identified in Cassini near-

Figure 2.2-8. *Cassini radar image at 350 m resolution showing broad valleys cutting through over a hundred kilometers of rough terrain in Xanadu on Titan.*

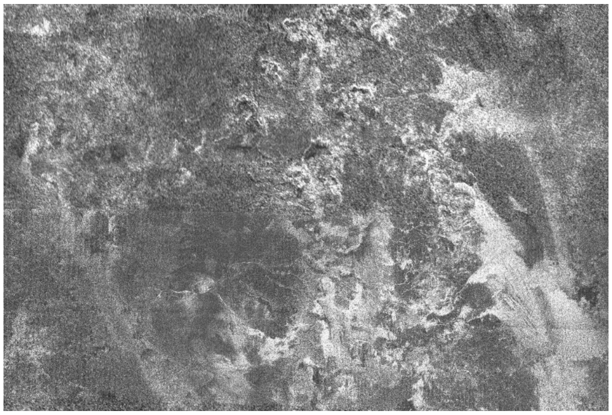


Figure 2.2-9. This area around Ganesha Macula (circular feature with a central caldera on the lower right) appears much like volcanic features on Earth or Venus do to imaging radar. This is one of the most promising candidates for a cryovolcanic feature on Titan. Image from Cassini radar is 570 km wide.

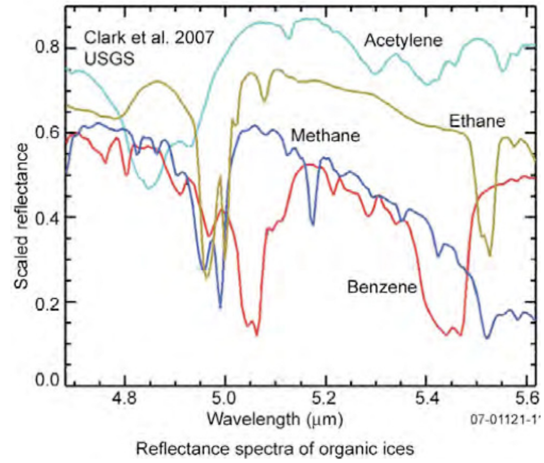


Figure 2.2-10. Hydrocarbon features between 5 and 6 μm are not observable by Cassini.

infrared (Sotin et al. 2005) and radar (Lopes et al. 2007) images (**Figure 2.2-9**). Although evidence for active volcanism has not yet been widely convincing, there are apparent surface changes in Cassini data that require explanation (e.g., Nelson 2007).

Initial altimeter observations suggested that Titan may be rather flat (elevation changes of only a few tens of meters over hundreds of kilometers). Indeed, some sedimentary basins appear to be this flat, but Titan in fact shows substantial relief. Mountain chains with heights of 700 m+ have been measured (e.g., Radebaugh et al. 2007), and crater Sinlap is known to be 1300 m deep. As more data arrive, it is clear that Titan in fact has substantial topography (>1 km) on a variety of length scales. Cassini is not well-equipped to generate a global topography dataset, and generating such data is a key goal for a follow-on mission, not only for geological studies but also as a boundary condition for circulation models.

An important Cassini finding needs to be underscored—at all spatial scales, there are structures seen in radar images that correlate with those in the near-IR, and there are structures that do not correlate at all. Radar and optical data thus tell us very complementary things about Titan's surface, and consequently a follow-on mission requires high-resolution global coverage by both techniques. In the near-IR, high-resolution coverage is particularly lacking from Cassini because of the short, rapid flybys and limited sensitivity of VIMS. While the surface is spectrally diverse, the identification of surface materials in the spectral windows Cassini VIMS is able to observe with its near-infrared channel (from 0.85–5.1 μm wavelength) has proven challenging. This makes extension to longer wavelength (5.8 μm; **Figure 2.2-10**) and higher spectral and spatial resolution highly desirable.

2.2.4 Titan's Organic Chemistry and Astrobiology

The Cassini-Huygens era of investigation has furthered our understanding of Titan as the largest abiotic organic factory in the solar system. The abundance of methane and its organic products in the atmosphere, seas and dunes exceeds by more than an order of magnitude the carbon inventory in the Earth's ocean, biosphere and fossil fuel reservoirs (Lorenz et al. 2008a). Mass spectrometry in the upper atmosphere has shown that the process of aerosol formation appears to start more than 1000 km above the surface through a complex interplay of ion and neutral chemistry initiated by energetic photon and particle bombardment of the atmosphere (Waite et al. 2007), and includes polymers of high molecular weight—up to and certainly beyond C_7 hydrocarbons that the Cassini mass spectrometer was able to measure. Measurements throughout the atmosphere, both remotely and

in situ, have indicated the presence of numerous hydrocarbon and nitrile gases, as well as a complex layering of organic aerosols that persists all the way down to the surface of the moon (Coustenis et al. 2007; Tomasko et al. 2005), including in the low atmosphere aerosols, (Israel et al. 2005) although their molecular composition has still to be determined. Radar observations suggest that the ultimate fate of this aerosol precipitate is the generation of expansive organic dunes that produce an equatorial belt around the surface. These sand dunes are remarkable in being exactly the same size and shape as linear (longitudinal) dunes on Earth (Lorenz et al. 2006) such as those found in the Namib and Saharan deserts. This type of dune forms in a fluctuating wind regime, which on Titan may be provided by the tides in the atmosphere due to Saturn's gravitation acting over Titan's eccentric orbit.

While the chemical reactions that drive living things take place in liquid water, the reactions themselves are almost entirely between organic (i.e., carbon-bearing) compounds. The study of organic chemistry is an important, and arguably richer, adjunct to the pursuit of liquid water in the solar system. Titan's organic inventory is, as noted above, nothing short of massive, and organic compounds are widespread across the surface in the form of lakes, seas, dunes and probably sedimentary deltas at the mouths of channels.

In Titan's present atmosphere, with little oxygen, photochemistry alone is something of an evolutionary dead end, in that only hydrocarbons and nitriles (i.e., H, C, and N-bearing molecules) are formed in any abundance. Little oxygen comes in from space, and most of that ends up in the form of carbon monoxide in the atmosphere.

However, as noted by Thompson and Sagan (1992), tholins deposited on Titan's surface may be able to take the next evolutionary step by reacting with transient exposures of liquid water, namely impact melt and cryovolcanism. Subsequent work has confirmed that such geological structures would indeed permit aqueous chemistry to occur for centuries or longer (e.g., O'Brien et al. 2005; Neish et al. 2006). Laboratory experiments have shown that the interaction of water with tholins can yield amino acids in substantial amounts—roughly 1% by mass (e.g., Khare et al. 1986; McDonald et al. 1994). Simpler nitriles have been detected in the gas phase on Titan (and indeed in the solid phase [Khanna 2005]). These nitriles will be deposited as condensate on the surface and also can react to form astrobiologically interesting material in water. For example, Ferris et al. (1978) show that moderately concentrated HCN solutions can hydrolyze to form oligomers that in turn yield amino acids and pyrimidines. (Purines and pyrimidines—organic rings with some substitution of carbon atoms by nitrogen—form the bases that encode information in DNA in terrestrial living things; this information is used to determine the sequence of amino acids used to assemble into proteins.)

The temperature- and pH-dependence of the rates and yields of these reactions remain poorly known, both for lack of laboratory data and because Titan reactions may happen on geological timescales that cannot be reproduced on Earth, at least not on conventional research timescales. Other factors (e.g., inorganic catalysts, or the pressure and concentration enhancements that can occur at a freezing front) may accelerate these reaction rates. For example, Takenaka et al. (1996) explored how freezing can accelerate, by a factor of 100,000, the oxidation of nitrite by dissolved oxygen to form nitrate.

Specific geological sites such as the floors of impact features and the margins of cryovolcanic flows would of course be of particular interest for these investigations, but data at the scale of Cassini (or even an orbiter) do not permit confident determination of the ease of landing or acquiring desired samples. However, the ample evidence of fluvial and aeolian transport on Titan suggests that sediments everywhere likely contain a component of eroded material from such structures. Therefore, *in situ* sampling locations that are large in scale and are likely repositories of such sediments is of high priority. Two such promising locations are the equatorial dunes, which are likely a vast repository of organic sediments (Radebaugh et al. 2007) and the two large northern hemisphere seas, which if composed of ethane (Brown et al. 2008) and methane could contain within them analyzable amounts (Raulin 1987; Dubouloz et al. 1989) of dissolved organics from elsewhere on Titan.

The extent to which present-day Titan resembles the prebiotic Earth is not clear, since the oxidation state of the early Earth is not well determined. Certainly the present Titan is more oxygen-poor than was Earth, but formation of organic haze may nonetheless have taken place on our own planet early in its history. Trainer et al. (2004) show that organic haze formation under UV illumination takes place as long as the carbon to oxygen ratio is above about 0.6, and methane photolysis on the early Earth would have provided a richer organic feedstock than the delivery of organics from meteorites. In addition to the prebiotic synthesis role, haze on the early Earth may have been significant in the radiative balance (acting as an anti-greenhouse agent) and in particular in providing UV opacity which may have protected nascent biota in the absence of an ozone shield. Thus, while the analogy of Titan to the early Earth is not perfect, it is potentially quite close. Titan-like planets may be common in the universe—indeed planets around the most common stellar type, the cool M dwarfs, at the distance of the Earth from the Sun will be as cold as Titan. Titan may usefully inform us about their organic chemistry and potential habitability.

Titan is highly complementary with Mars in origins of life questions, in that Mars is an oxygen- and water-rich body, with little organic carbon, while Titan is an organic-rich body with little available oxygen. Europa is at least water-rich, but its formation history likely prevented the incorporation of much carbon.

The surface of Titan appears at first glance to be an unlikely location for extant life, at least terrestrial-type life. McKay and Smith (2005) have noted that there are photochemically derived sources of free energy on Titan's surface which could support life, which would have to be an exotic type of life using liquid hydrocarbons as solvents (Committee on the Origin and Evolution of Life 2007). In a similar vein, Stoker et al. (1990) observed that terrestrial bacteria can in fact derive their energy and carbon needs by 'eating' tholins. In this sense, a methane-rich atmosphere may act as a 'poor-planet's photosynthesis', providing a means to capture the free energy from ultraviolet light and make it available for metabolic reactions. Benner et al. (2005) have speculated that a form of life, or at a minimum a kind of organized chemical system, can be sustained in liquid hydrocarbons known to be stable on Titan's surface; the National Academy of Sciences report "The Limits of Organic Life in Planetary Systems" (2007) emphasized the importance the discovery of such a system would imply. Finally, Fortes (2000) argued that life could have gained a foothold in Titan's subsurface ocean, and evidence of such organic material could be driven to the surface in cryovolcanic events and preserved in the cold, radiation-free surface environment.

2.2.5 Evolution and Interaction with the Saturn System

The evolution of Titan's atmosphere operates on two quite different time scales. The longest time scale represented is the billion-year time scale commensurate with the origin and subsequent evolution of the overall system. This time scale is best studied by measuring the noble gas concentrations and their isotopic abundances, as well as the nitrogen and carbon stable isotope ratios. Cassini-Huygens has provided some important information in this regard. The abundance of the radioactively derived ^{40}Ar has indicated that only a few percent of the total volatile inventory has been outgassed from the interior (Waite et al. 2005; Niemann et al. 2005). Whereas, the relatively low abundance of the primordial ^{36}Ar isotope suggests that nitrogen was not delivered during Titan's initial formation as molecular nitrogen, but more likely as ammonia that underwent subsequent chemical conversion into N_2—the predominant constituent of Titan's present day atmosphere. Furthermore, the enrichment of ^{15}N to ^{14}N in N_2 relative to an earth reference suggest that as at Mars Titan has lost most of its nitrogen over the course of its evolution (Waite et al. 2005). This is substantiated by the measurement of isotopic separation in the upper atmosphere measured by the Cassini INMS and the escape of methane and hydrogen inferred from the altitude structure of these species in Titan's upper atmosphere (Yelle et al. 2005; and unpublished data analysis from Cassini INMS) and the modeling of hydrodynamic escape processes by Strobel (2008). Measurement of the isotopic ratios of other noble gases such as those of neon, krypton, and xenon will provide important clues about the overall role of escape in the evolution of Titan's atmosphere,

but must await new surface analysis techniques such as noble gas enrichment cells, which were not present on the Huygens GCMS (Niemann et al. 2005).

Escape processes can also be understood via *in situ* sampling of the plasma and energetic particle environment surrounding Titan and resulting from the interaction of Saturn's magnetospheric particles with the thick upper atmosphere of Titan This study that began during the Cassini-Huygens mission will benefit greatly from an orbital mission that samples the atmosphere near the exobase as proposed for the mapping phase of the proposed Titan mission. Here a complement of plasma, fields, and energetic particles experiments will be able to determine the three-dimensional structure of the sputtering interactions that leads to the heating and erosion of the upper atmosphere (De La Haye et al. 2007). By understanding the physics of these processes, it will be possible to extrapolate the escape processes back in time to appreciate their impact on the evolution of the Titan system.

The second time scale of relevance at Titan is the timescale for the irreversible conversion of the methane in the atmosphere into higher order organic/nitrile compounds that eventually end up deposited on the surface of Titan. The irreversibility argument ties back to the escape of hydrogen from the system, so that for each molecule of methane that is photolyzed, a molecular hydrogen molecule escapes. Given the present rate of photolysis and energetic particle induced conversion processes and the size of the present atmospheric reservoir of methane the atmospheric methane will be completely converted to higher order organics in a 70 million year timescale if not replenished from the interior. Current escape rates for methane cut this time scale by a factor of two. Evidence for the replenishment of methane from interior processes is found by observing the ^{12}C to ^{13}C ratio forming the methane of the upper atmosphere. The measured value is near that of our terrestrial reference indicating that methane is resupplied and converted at a rate that prevents the buildup of the heavier isotope over time as is the case of nitrogen. The source of the resupply is a mystery that our future mission must address. Potential candidates include an evolving interior thermal history leading to episodic releases of methane over geological time, serpentinization processes in the interior, and perhaps reprocessing of higher order organics that have been buried by surface geological processes (see Atreya et al. 2006 for further discussion).

Cassini INMS measurements of methane and ^{40}Ar (radiogenic argon) in the upper atmosphere have been used to determine the rate of vertical mixing and the escape flux of methane from Titan's atmosphere (Yelle et al. 2008). Surprisingly, the measurements indicate a much higher escape flux than previously thought, roughly 13% of the photochemical destruction rate, and must be treated as hydrodynamic rather than with the Jeans approximation. Thus, there might conceivably be times in Titan's history when the escape rate is competitive with the photochemical destruction rate. The result reinforces the transient nature of methane in Titan's atmosphere, the need to identify potential sources of methane that maintain its presence on the surface over geologic time, as well as the need to re-evaluate the implications for interpreting the isotopic ratio of carbon in methane in terms of methane's origin. This very new result illustrates that the basic physics of Titan's atmosphere remains surprising, and that new instrumentation from a Titan orbiter is likely to yield new surprises.

In any event the methane/nitrogen conversion process that begins in Titan's upper atmosphere via ion neutral chemistry and leads to the creation of minor higher carbon and nitrile gases and their aerosol counterparts throughout the stratosphere is a story whose basic features have been revealed by Cassini-Huygens (Tomasko et al. 2005; Coustenis et al. 2007; Waite et al. 2007), but which begs for a follow up mission to understand the secrets of the most active abiotic organic factory in the solar system and the ultimate fate of organic residues on its surface.

2.2.6 Enceladus

Enceladus, a 500 km diameter moon of Saturn, is one of the most remarkable bodies in the solar system (**Figure 2.2-11**). It is the only icy world in the solar system proven to have current geological activity (excluding Triton's geysers, likely solar-driven), offers the possi-

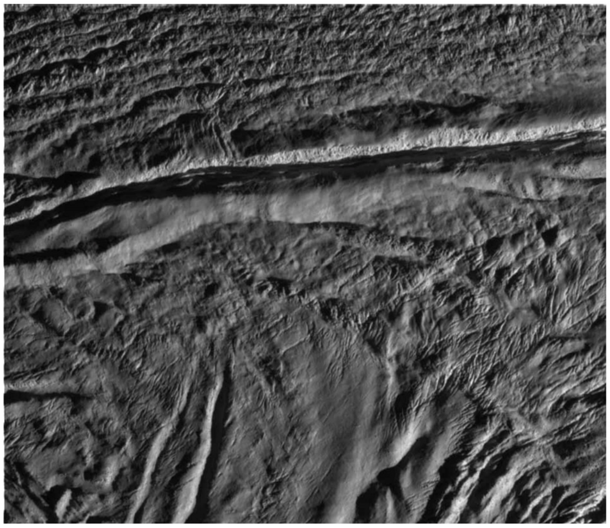


Figure 2.2-11. *Complex terrain near the south pole of Saturn's active moon Enceladus, imaged by the Cassini orbiter with a resolution of 30 m. Cutting across the scene just above the center of the image is Damascus Sulcus, one of the sources of the active plumes sampled by the Cassini INMS. (NASA/JPL/SSI)*

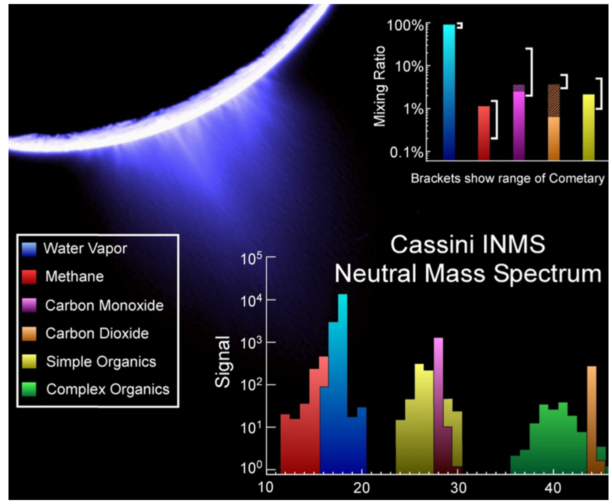


Figure 2.2-12. *Schematic based on Cassini INMS data showing the classes of compounds detected coming out of the Enceladus plumes by the Cassini INMS instrument, with a comparison (top) to values measured in comets. Background ISS image shows the plumes at the south pole of Enceladus.*

bly of biological potential, and provides a way to sample fresh material from its interior via active plumes that have been discovered and observed by multiple instruments on the Cassini orbiter (See the series of articles in the *Science* special section on Enceladus, 10 March 2006).

These plumes contain water, carbon dioxide, methane, and other organic molecules; they are also the source of Saturn's E-ring. Cassini data as yet do not provide definitive constraints on whether the plume source region within Enceladus contains liquid water or simply warm ice; models exist that generate plumes from either (Nimmo et al. 2007; Kieffer et al. 2006). Cassini observations during its extended mission may resolve this issue, particularly if elements such as sodium (soluble in liquid water and not ice) are identified in or near the plumes. A hint that sodium might in fact be found eventually in the Enceladus plumes comes from its detection in E-ring particles by the Cosmic Dust Analyzer (Postberg et al. 2008). The source of the E-ring is known to be Enceladus' plumes based on images from the Cassini orbiter, and the sodium detected in the particles likely came from Enceladus. However, direct detection in the plumes is a more rigorous test of whether sodium originated in the subsurface, and would further support the presence of a subcrustal liquid water layer.

If the plume source region on Enceladus is liquid water, then it provides a plausible site for complex organic chemistry (Matson et al. 2007) and even biological processes (**Figure 2.2-12**). Samples from this environment can be obtained by flying past Enceladus through its plume; Cassini has done so but is limited in its ability to detect compounds of high molecular weight and hence indicative of complex organic chemistry. An advanced mass spectrometer to detect and characterize such compounds can be carried on the next mission to the Saturn system.

Enceladus' plumes provide us with an opportunity to study today phenomena that have been important at some time in the past throughout the outer solar system, when tidal effects and/or higher radiogenic heat fluxes may have powered geysering, melting and aqueous chemistry in a number of icy bodies. Also, because Enceladus is the source of the Saturnian E-ring (**Figure 2.2-13**), as well as the extensive neutral O and OH clouds that fill the middle Saturnian magnetosphere, the moon plays a pivotal role in the Saturnian system,

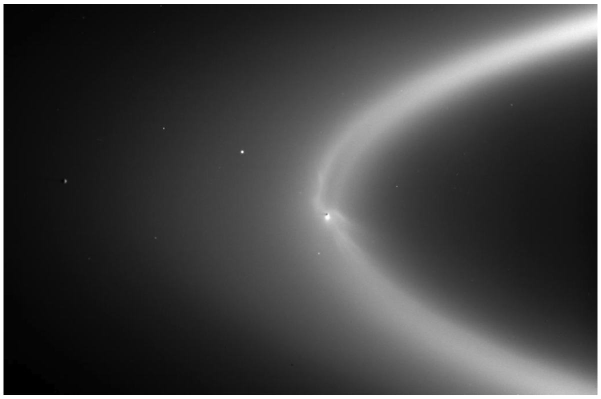


Figure 2.2-13. Cassini image showing Enceladus (near center), throwing off material (wings on either side of moon) that resupplies the tenuous E-ring within which it is embedded. ISS image (NASA/Space Science Inst.)

similar in some ways to Io's role in the Jovian system.

Enceladus' plumes are its most important feature. They allow us to obtain samples directly from the interior. They provide information about the initial composition of the kronian nebular material from which Enceladus and Titan accreted. This is truly a unique opportunity for measuring samples from an icy moon's interior *in situ*.

The plumes must be placed, of course, in the broader context of Enceladus' geologic history. The big event after formation was differentiation and the subsequent resurfacing with very clean ice. Enceladus has the highest reflectivity (albedo) of any natural satellite. There were multiple episodes of resurfacing, as shown by the range of crater densities across Enceladus' surface. Heavily cratered units are perhaps billions of years old whereas the youngest, the south-polar region, is probably less than ten million years old. The interior became hot, 500 to 800 K, as inferred from the presence of molecular nitrogen in the plume (Matson et al. 2007) and further sustained by the discovery of sodium rich grains in the E-ring (Postberg et al. 2008). These are conditions ideal for the synthesis of complex, organic molecules and may also have occurred in Titan. TSSM will directly address these processes through its analysis of plume samples.

Close to the surface there have been a number of models proposed for structure and heat production (e.g., Kieffer et al. 2006; Nimmo and Pappalardo 2006; Nimmo et al. 2007; Collins and Goodman 2007; Tobie et al. 2008; and others). While the Cassini data should be sufficient for resolving competing issues between models for structure, the higher sensitivity and spatial resolution for measuring thermal emission will be important for constraining the mechanisms by which heat is produced in Enceladus.

Although study of Enceladus by itself is rewarding, this moon is also attractive in the context of TSSM for its relevance to understanding Titan. Both are ice-rock objects, with roughly the same rock to ice ratio, and both almost certainly were formed in the Saturn system. Enceladus' active geysers provide a window into the interior of a Saturnian moon that Titan's huge atmosphere and more complex surface geology and sedimentation cannot.

With Enceladus, there is an opportunity to sample materials that are relevant to Titan's initial inventory and evolution but less accessible in Saturn's giant moon. For example, the question of whether much of the methane within Titan's interior was manufactured by so-called serpentinization (Glein and Shock 2007) or acquired primordially is beginning to be addressed through measurement of the carbon budget in the plumes, which includes both CO_2 and CH_4. Relating the two bodies to each other will require measurement of isotopic ratios in primary carbon species as well as—if possible—detection of noble gases and nitrogen-bearing species in the plume material coming from Enceladus. This will require a higher resolution mass spectrometer than on Cassini-Huygens. The ability to study geologic processes on sister moons of similar ice-rock ratio but three orders of magnitude difference in mass will provide a unique insight into how sources of heating manifest themselves in surface activity and tectonics on rock-ice worlds.

Finally, there may be a direct connection between Enceladus' plumes and the oxygen chemistry in Titan's upper atmosphere. The dominant oxygen-bearing gas in Titan's atmosphere is CO, which at 50 parts per million is likely derived from the methane-dominated hydrocarbon chemistry and an external source of oxygen (e.g., Wilson and Atreya 2004). Although water from micrometeoroids precipi-

tates into Titan's atmosphere (Coustenis et al. 1998) this source is not sufficient by itself to explain simultaneously the abundances of CO and CO_2 (Horst et al. 2008).

Instead, Cassini CAPS observations revealed O^+ ions precipitating into Titan's atmosphere (Hartle et al. 2006), and chemical modeling shows that a combination of atomic oxygen sources and water (or OH) are required to explain the origins of both atmospheric CO and CO_2 without invoking outgassing from the interior of CO (there may still be patches of internally derived CO_2, but these do not reach the upper atmosphere given the very low tropopause temperature, Samuelson 1983).

Cassini observations of the Enceladus plumes indicate that they are the dominant source of O^+, O_2^+, and OH, derived from water coming out of the vents (Waite et al. 2006, and other papers on the plumes). The water-ice dominated plumes coming out of Enceladus' interior, magnetospheric processes that transform some of this material into oxygen atoms and ions, and the oxygen chemistry producing CO and CO_2 in Titan's atmosphere are coupled.

2.3 Mission Goals, Science Objectives, and Investigations

2.3.1 Introduction

An international science and technical team was formed with the goal of developing a focused, cost-effective mission that would address the key questions about Titan left by Cassini-Huygens and have the capability to make new discoveries not possible with that mission. NASA and ESA formed a Joint Science Definition Team (JSDT) with 16 US and 15 European members. This JSDT agreed upon established goals and science objectives that they derived from (a) the SDT assembled last year by NASA to study a mission to Titan, modified by the NASA terms of reference for the present study, (b) from the TandEM study conducted last year in Europe, (c) the latest results of Cassini-Huygens, and (d) supporting documents such as the National Academy Decadal Survey. The current JSDT generated the science investigations, measurement requirements and approaches necessary to achieve these goals.

The JSDT also selected the *in situ* elements. Early in the process it was recognized that mobility in the atmosphere would be important for addressing many of the questions remaining after Cassini-Huygens. It was also recognized that some form of surface sampling was highly desirable. The JSDT examined possible landing sites that would achieve the objectives of landed science within the 400 km by 160 km landing ellipse. Unlike Huygens, "anywhere" is not acceptable because the instrument package must be able to sample organics, one of the major landed objectives. Two very large types of terrain satisfy the objectives: the dune fields, which stretch for thousands of kilometers at the equator, and the largest northern hemisphere lakes, which are sufficiently big to encompass the error ellipse for landing. The dunes were ruled out because acquisition of a sample would require a complex system, possibly involving ejection from the lander or with a long arm. The lakes were determined to be ideal because sample injection requires only a tube to equalize pressure and a membrane to control flow. The lake site is also more interesting because the solubility of organics and noble gases in liquid ethane and methane as measured in the laboratory is high enough that the lakes are a kind of natural collection system for the global organic inventory, and for noble gases that tell us about origins. Another advantage is that by being near the poles, a magnetometer system on the lake lander will be able to better complement the measurements by the montgolfière in the equatorial region. Landing safety and communications are also simplified because the lander will not be tilted or occulted by slopes as could be a problem in the dunes. The one area of science that cannot be done on the lakes is seismometry, but the weight and complexity of the sampling systems for organics on the dune lander might have precluded the presence of other instruments anyway. The potential of instrumenting the montgolfière heat shield with a simple seismometer that would sit at low latitudes was identified by the JSDT and is currently being studied by ESA.

The remainder of this section shows how the goals and objectives were developed and how they in turn define the required measurements; these are used to define a planning payload and technical requirements on the mission as described in §2.4. Section 2.3 is organized as follows: the outstanding issues

about Titan and the aspects of the Saturn system relevant to understanding Titan based on our current understanding (discussed in §2.2) are summarized in §2.3.2. Section 2.3.3 describes the basic structure and logical flow of the traceability matrices that are the primary tool for determining the instrument payloads and their capabilities. In §2.3.4, the formulation of the mission goals is described.

The heritage of guiding documents that go back to the Decadal Survey of the National Academy of Sciences is summarized in §2.3.5, along with an assessment of how the mission that is described in the rest of the report measures up against the Decadal Survey and more recent studies.

A tour through the logical flow of the traceability matrices, starting from the mission goals which are divided into a set of science objectives, which in turn motivate a series of science investigations common to the orbiter and the *in situ* elements that are the basic architecture of the mission is found in §2.3.6. The types of measurements and requirements on these measurements needed to fulfill the science investigations are then described. The measurement requirements for the orbiter and *in situ* elements provide the specifications needed to develop planning payloads for each of these components of the mission, and those payloads are given in §2.4.

2.3.2 Key Questions to be Addressed by TSSM

For brevity's sake this narrative takes off directly from the science summary of §2.2, and no attempt is made to provide citations to the literature (see §2.2 for those). At the core of Titan's nature is the role of methane from its breakup and chemistry in the upper atmosphere through the methane cycle in the lower atmosphere and surface to its storage in the crust and deep interior. It is convenient, then, to proceed downward from Titan's uppermost atmosphere to the interior.

Upper Atmosphere and Magnetosphere

Cassini's brief flybys provide only piecemeal estimates of the atmospheric loss rates of methane and its products from photochemistry and energetic particle chemistry. The nature of Titan's ionosphere in terms of its three-dimensional structure is not known and not achievable with Cassini. How does the ionosphere form and what is the variation in exchange of species and energy with the Saturn magnetosphere? What happens to the ionosphere as Titan passes in and out of the solar wind?

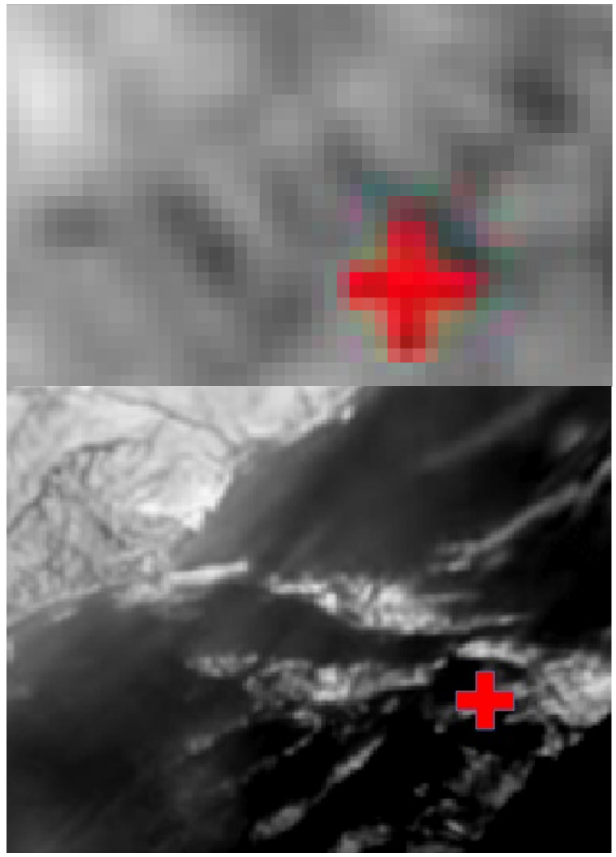


Figure 2.3-1. *Huygens landing site from radar at 1 km resolution (top) and from DISR image at 50 m resolution (bottom). [The size of the cross is not significant; it marks the Huygens landing point and was part of the jpeg of the radar image].*

Cassini data hint at direct escape of methane being competitive with loss by photochemistry. This is paradigm changing, but is based on indirect derivation of vertical mixing in the upper atmosphere from the profile of radiogenic argon above 900 km. What is the vertical profile of methane below the escape level, in the region from 400–900 km where transport of molecules and chemistry is very poorly known? If methane escape is more important than previously thought, what does this imply about the escape rate of the primary atmospheric gas nitrogen, which based on Voyager estimates is about 10% of the total in

the atmosphere over the age of the solar system? Might the loss be larger?

The discovery by Cassini that products of the charged particle chemistry in Titan's upper atmosphere decline only weakly with molecular weight implies that there are heavy organic polymers formed at very high altitudes, which Cassini cannot detect. The chemistry here is of keen interest not only in understanding the entirety of carbon chemistry on Titan, but also in understanding the chemistry of heavy molecules that on Earth might have played a role in the origin of life. What are the nature and abundance of the heavy organic polymers formed in Titan's upper atmosphere? Does the small amount of oxygen available participate in some way? What is the role of these compounds in the formation of aerosols and do they provide sites for accelerating gas phase chemistry as they sink through the lower reaches of the atmosphere?

Despite the overall lack of oxygen, there is a photochemical and energetic-particle-chemical cycle of CO and CO_2, whose ultimate sources appears to include oxygen from the ice plumes of Enceladus as well as contributions from meteoritic water. The formation of CO_2 is particularly sensitive to the distribution of O and OH through the very poorly observed region from 400–900 km in altitude, largely inaccessible to Cassini. How does the oxygen-bearing component of Titan's carbon chemistry work? How much CO_2 is produced in this fashion? What is the dependence on Enceladus? Other issues associated with this region—the absorption of solar UV and consequent thermal structure of this chemically-active region—will not be adequately quantified by Cassini.

Cassini has provided us with a glimpse of the formation of aerosols in the upper atmosphere, but the role of ions in aiding aerosol formation requires much more detailed observations. There are fundamentally important issues associated with the nature of Titan's aerosols, including their role in absorption of sunlight and heating of Titan's atmosphere, their growth and sedimentation, their role recently suggested by laboratory studies that they can sequester and hence hide noble gases, and even more exotic possibilities that they could aid in chemically recycling a small amount of the methane destroyed by photochemistry and increase the lifetime of methane in the atmosphere (countering the decrease in methane lifetime thanks to escape, as described above). Essentially, the aerosols are the results of transforming methane and nitrogen (using the energy that impinges on Titan) into organic products that participate in surface processes, from ethane in the seas to the organic products in the dunes. Aerosols may even provide a surface storage medium for UV and charged particle energy through the formation of products like acetylene that can undergo exothermic reactions later on Titan's surface.

A raft of questions on the aerosols exists that require a broad range of types of observations not possible from Cassini. What is the role of ions in aerosol formation? Do the profiles of the isotopes of argon suggest a role for aerosols in trapping of noble gases? How does the winter ethane stratospheric cloud form and is the primary means for sequestering ethane after formation? How does growth and sedimentation of aerosols proceed? What is their state and evolution on the surface? How do the gaseous and condensed phases interact in the atmosphere as a function of altitude, location and time? Are the aerosols a significant sink of noble gases, as suggested by lab data; or even of ethane?

Lower Atmosphere and Surface

In the middle and lower atmosphere of Titan, winds carry solar energy transformed into heat from equator to pole. Cassini has measured the thermal structure of the lower atmosphere in various locations, including the poles, but energy is carried as well in the middle part of the atmosphere above 400 km where almost no information has been obtained. What is the circulation in this region? Even below, the dynamics of the so-called Hadley circulation from equator to pole is highly uncertain, and a shift in the rotation rate of Titan caused by the atmosphere—observable because the crust is decoupled from the deep interior by a liquid layer—reveals an unexpected time-lag in Titan's seasonal spin rate. Is this lag the result of an active cycle of methane weather in the atmosphere which damps the seasonal cycle of solar forcing? What is the nature of this annual weather system, and is it confined largely to polar methane cloud formation or do convec-

tive clouds form at mid-latitudes as hinted by Earth-based observations? What is the detailed morphology of springtime/summer cloud features at the poles? What role do surface methane reservoirs play in latent heat and methane vapor supply and transport? Coverage by *in situ* elements that can probe the clouds directly and synoptic coverage by an orbiter capable of remote sensing at all levels will be required to quantify the nature of Titan's meteorology.

Titan's surface is perhaps it's most enigmatic and fascinating feature. In only one location—where the Huygens probe drifted at low altitude and then landed—are there high resolution images of the surface. And yet in that small region are seen the effects of liquids carving the landscape, dunes in the distance, hills that speak of planetary tectonics, and a teaser of liquid methane that flowed from the ground into the probe as it sat on a plain dotted with rounded (ice?) cobbles. The remainder of the surface is seen at best at 300–500 m resolution, and here only of order 10–20% of what evidently is a varied and complex world—most of Titan is seen at 1 km and worse. At resolution of hundreds of meters, dunes are positively identified, areas of likely lakes and seas, and broad fluvial valleys, but a raft of surface features ranging from enigmatic circles hundreds of meters across to mountains to possible lava flows are seen but not understood. The rule of thumb that has served well in 40 years of planetary exploration is that roughly a factor of 10–20 improvement in resolution from one mission to the next is an optimal compromise between getting surface detail and having manageable data volumes to enable a realistic mission (**Figure 2.3-1**).

With the images at hand one can ask a long list of questions: Do the broad fluvial valleys branch into fine dendritic features like those seen at the Huygens landing site? What geologic process—impact, volcanic or otherwise—forms the circular features seen in many radar images? What is the nature of the topographic features that interrupt the dunes? Are the features that look like lava flows in fact cryovolcanic flows? What do the shorelines of the lakes look like—are there sediments on the shorelines, or precipitates of some variety? Are the mountains incised with small-scale channels? And so forth.

Equally ambiguous is the determination of the chemical composition of the surface and of the lakes. Hydrocarbon and nitrile spectral features are seen from Cassini but the spatial resolution is coarse and the compounds responsible are not identified. At the Huygens landing site higher resolution spectra extended only to 1.5 μm, whereas spectra out beyond 5 μm is required to separate various hydrocarbons and organic molecules. Is the chemical composition of the surface correlated with geology in some way? Has acetylene reacted and transformed into other compounds, releasing stored energetic particle and UV energy derived from the high atmosphere? What is the bulk composition of the northern hemisphere lakes? Is methane present in the south's Ontario Lacus in addition to the already identified ethane? Is there evidence for the formation of organics, particularly oxygen-bearing organics, in discrete places on Titan's surface? Is there evidence for interaction between organics and liquid water formed during impacts or cryovolcanism? Are sources of energy for continued evolution of organics available on Titan's surface, such as current cryovolcanism?

Saturn's moon Enceladus provides a second site for testing how far organic chemistry proceeds in the presence of liquid water, assuming that the observed plumes have liquid water at their source. Is there liquid water in Enceladus? Do high molecular weight polymers appear in the plumes? Are oxygen-bearing organics present in the plumes?

Together with images and compositional information, topography is essential for understanding the nature of features on a planetary surface. Cassini was very limited in the topographic information it could derive by various means, and over the vast majority of the planet little or nothing is known about the topography. Why the rivers flow in the direction they do on Xanadu is not understood because the topography is too crude to determine slope directions. The topographic shape of Ganesha Macula, based on Cassini data, does not seem consistent with its interpretation as a cryovolcano, but the altimetric data are crude. Is it a topographic high? What is the topography along the lake shorelines? Are the various lakes in the northern hemisphere at different heights or at a constant level suggestive of the equivalent of a methane aquifer?

The overall sources and sinks of the methane remain poorly understood after Cassini-Huygens, which has eliminated one possible reservoir—a global surface ocean—and hinted at the possibility that methane is stored in a porous ice crust. Some insight into the possibility of a methane (and ethane aquifer) will come from watching the northern hemisphere lakes as the seasons' progress: whether they wax and wane in a manner consistent with isolated basins or are stably supported by a larger underground reservoir. This is an indirect approach, however, and more direct approaches are required to answer whether the crust can or does contain large amounts of methane and/or its product ethane.

Titan's Interior

Titan's interior also remains poorly constrained at the moment. Determination of the interior structure by the usual technique involving tracking of the spacecraft radio signal has been hampered by the effects of drag on the spacecraft, although some success has been made in determining that Titan's moment of inertia is consistent with some degree of differentiation into a rocky core and an icy mantle. More sensitive radio science measurements, with a means of removing the effects of atmospheric drag, will be required to make more progress. The determination that Titan's crust is decoupled from the bulk of its interior was made from observing the asynchroneity in Titan's rotation rate, but because this is an indirect means of detecting an interior ocean (the liquid layer decoupling the crust from the interior), other tests should be made. How thick is Titan's icy crust? Is the interior below the liquid layer fully differentiated into a high pressure ice mantle and a rocky core? What can the thermal history of Enceladus—close in density to Titan but 1000 times less massive-teach us about the thermal evolution of much larger satellites like Titan?

An intrinsic magnetic field inside Titan—one generated by a dynamo deep in the interior—appears to be absent, but detection is hampered both by the large distance at which Cassini must fly by Titan, and the presence of a shielding ionosphere. It is even more difficult, for the same reasons, to detect a magnetic field induced by the presence of the Saturnian magnetic field. If the ocean is salty, which is possible given that during its formation it was almost certainly in contact with rock in the interior—there should be an induced field, though weak because the Saturnian magnetic field at Titan's orbit is very weak. Answering whether Titan has either type of field cannot be determined with adequate sensitivity by Cassini.

Titan's Origin and Evolution

Having proceeded downward from the upper atmosphere to the deep interior Titan must now be considered in time. Cassini will provide information on seasonal variations in the atmosphere for almost 2/3 of a Saturn year if it survives to 2017, which is possible. This will allow a number of questions about the southern polar region to be addressed. Why did Cassini not see many lakes in the southern hemisphere? Do basins in the south fill with liquid in the winter? Does the onset of summer trigger the convective storms seen by Cassini later in the summer? What other seasonal processes are asymmetric between the north and south.

On longer timescales the atmosphere may become moist in methane if the equivalent of a terrestrial aquifer exists beneath the high latitude lakes. Are there such aquifers? Are there meteorological processes indicative of a gradual humidification of the atmosphere with time? Do convective storms form at low latitudes in spite of the dry conditions?

Over geologic time Titan has evolved, cooling and thickening its crust. Is there evidence for crustal thickening over time? What is the present-day crustal thickness? Has it thickened recently, or has it been thick throughout the history of Titan? Is there evidence for present-day or recent volcanism, or active geysering of methane, on the surface? Are there reservoirs of ethane or methane that might be detected through crustal profiling or higher resolution imagery or spectroscopy than has been possible to date?

Finally, how did Titan form? What is the origin of its methane? Was it derived from carbon dioxide or from methane—that is, are there patches of carbon dioxide associated with evident cryovolcanic constructs on the surface? The low abundance of argon from Cassini suggests that nitrogen originated as ammonia, but ammonia has yet to be detected

on the surface. Why is krypton absent as well? Is it trapped in aerosols which sediment out to the surface? Are there dissolved reservoirs of noble gases in the lakes? Are there clues in the noble gas abundances, isotopic ratios of major carbon and nitrogen-bearing species, to whether the composition of the circum-Saturnian disk during the ringed planet's formation was distinct from that in the solar nebula? These questions require higher spatial and spectral resolution compositional measurements than Cassini could obtain. They also require exploration of the isotopic composition of the primary species emitted in the plumes of Enceladus; together the chemical and isotopic compositions of the major carbon and nitrogen bearing species in the two bodies may allow tighter constraints on the origin of Titan and the source of its volatiles.

Though lengthy, this section is not a complete list of questions derived from Cassini-Huygens. The lengthy list is not an indictment of Cassini-Huygens but an indication of how successful the mission was in surveying Titan and providing enough tantalizing information that raises more detailed questions. It will take a new mission to answer them, and the questions provide one basis along with the mission goals and objectives for formulating the science investigations and required measurements for such a mission described in §2.3.6.

2.3.3 Structure of the Traceability Matrices

The traceability matrices for the orbiter, lake lander, and montgolfière shown in **Tables 2.3-1**, **2.3-2**, and **2.3-3** (located at the end of §2.3) provide a flow from mission goals through scientific objectives, to measurement requirements and then specific measurement approaches. Satisfying these measurement requirements is the criterion for full mission success. The logic of the flow is as follows:

Mission Goals

The foundational goals, these are formulated as overarching questions that drive the basic design of a mission to Titan and the Saturn system. They recognize the two basic interests associated with exploring Titan. First, that Titan is a system of interconnected atmosphere, surface and interior that must be explored in the same way that other large bodies with atmospheres, such as Mars and the Earth, are explored. Second, Titan's surface and atmosphere are uniquely rich in organic molecules and active organic chemical processes, and provide a potential opportunity to study the steps leading to life's origin or even to discover an exotic form of life. The third goal arises from the NASA directive that the study encompass other objects in the Saturn system that are directly relevant to understanding Titan, and the JSDT has identified Enceladus and the Saturn magnetosphere as key in this regard.

Science Objectives

These are imperatives that, flowing from one of the mission goals, specify a major aspect of Titan to be characterized, or processes to be determined, by a series of science investigations. They were developed through examining the results of the Science Definition Team (SDT-1) activity in 2007 for the Titan Explorer study, the TandEM proposal to respond to the ESA Cosmic Visions Programme call, supporting documents such as the 2003 Decadal Survey, and overall results of the Cassini-Huygens mission.

The objectives are designed to be overaching enough that the resulting science investigations will cover Titan and the other relevant objects in the Saturn system in a comprehensive fashion.

Science Investigations

The science investigations refer to specific phenomena or problems to be addressed ("map interior structure of Titan," for example), that inform the more general science objectives and can be connected directly to a particular measurement or a set of measurements. They flow from the outstanding questions about Titan that remain after, or are derived from, the Cassini-Huygens mission as outlined in §2.3.2. Whereas the goals and objectives depend on the general nature of Titan as a planet-sized organic-rich world with an atmosphere, embedded within the Saturn system, the science investigations are written with the Cassini-Huygens results as their specific foundation and the outstanding questions raised by that mission as their motivation. They are logically organized via the science objectives.

Required Measurements/Determinations

These are a set of measurements that are required to adequately address the science investigations and are deemed to be feasible in the context of the next mission to Saturn. (For example, very elaborate measurements that would require completely new or unrealistic technologies were eliminated right off the top). They may or may not contain specifications such as spatial resolution, required particle energy range, etc., but are detailed enough to allow a planning payload to be designed with appropriate instrument capabilities to carry them out.

Planning Measurement Approach

This provides a specification of capabilities (spatial/spectral resolution, wavelength/energy range) that allows the required measurements to be addressed and planning instruments to be defined. These have a one-to-one relationship with the required measurements and are the link to the specific planning payload chosen.

Planning instrument acronym: The instrument on the planning payload that is designed to make the measurements outlined in the previous column. An overview of the instruments can be found in §2.4 with details on the instruments in §4.2.

Data products: The type of data and ranges of important parameters collected by the planning instrument.

Mission requirements: Constraints on spacecraft orbit, orientation or other mission parameters required to perform the observations.

The matrices for the orbiter and *in situ* elements are common up through the science objectives and many of the investigations are common. However, there are additional investigations on each of the *in situ* platforms. From here they diverge according to the types of measurements possible on each platform. The nature of the NASA Ground Rules (2008) and agreements among NASA and ESA for how to organize the reports are such that the detailed rationale for the required measurements is given only for the orbiter. In addition, §2.4 only details the orbiter planning payload. *However, the reader is urged to inspect the traceability matrices for the in situ elements as well*. More detail on the *in situ* element payloads is given in Appendix J.

2.3.4 Development of the Titan Mission Goals and Science Objectives

The mission goals and science objectives described below were developed from two primary and several secondary sources: 1) A set of goals and objectives was proposed by the NASA SDT-1, and 2) the European-US TandEM team did an essentially independent analysis that arrived at similar wording. The new goals and objectives reflect the current 2008 constraints imposed by NASA and ESA on the mission scope and cost, as well as the latest findings from Cassini-Huygens. They were constructed as well to ensure compatibility with, and traceability from, two primary guiding documents: The Decadal Survey of the National Academy of Sciences published in 2003, a report on the Limits of Organic Life published by the National Academy of Sciences in 2007, and NASA's Solar System Roadmap in 2006.

2.3.5 Traceability from Guiding Documents

Although the Final Report of the 2003 Decadal Survey recommended a mission to Europa as its highest priority, this represented a distillation of a very detailed analysis by the Large Satellites Panel, which concluded *that both Europa and Titan were their highest priorities*. They argued that Europa should go first for two reasons: (1) at the time, the Cassini-Huygens mission had yet to arrive at the Saturn system, and (2) they assigned merit to the notion that NASA should take turns sending spacecraft to the two giant planet systems (Saturn and Jupiter).

The Decadal Survey Large Satellites Panel developed a series of questions to be addressed regarding moons and their giant planets. On the basis of evaluating the merits of strawman missions to various targets with respect to how they addressed these questions, Europa and Titan came out on top. Because the present study (and the EJSM study, for that matter) are different from the strawman missions the Decadal Large Satellites panel created and evaluated, it was deemed necessary by NASA to have the study teams newly evaluate the ability of each mission to address the Decadal objectives. The rank verbiage that goes with each of the colors and numbers was developed at the request of NASA.

The primary evaluation exercise was done in a plenary session of the Titan JSDT at ESTEC in Noordwijk. One JSDT member did a separate and independent evaluation and came up with scores for orbiter-only and orbiter plus *in situ* within one or two tenths of what the plenary group obtained. Many of the scientists in the room had been involved in multiple previous missions and critically scored the science against the Decadal questions.

In the case of TSSM, there is an important caveat to the evaluation. Because Titan is in many respects a unique body in the outer solar system, more akin to a Mercury-sized terrestrial planet with atmosphere and hydrosphere, the ability of the mission to address the large satellite goals was considered with respect to Titan itself, and Enceladus insofar as it informs the origin and evolution of Titan (as stipulated in the NASA Ground Rules). It was NOT considered with respect to all the large satellites as a group. So, for example, since the Large Satellites Panel provided a duplicate set of questions for their "Theme 3: Exploring Organic Environments," one set being general and the other specific to Titan, TSSM was evaluated against the latter. Also, since the mission would visit Enceladus as well, where several important science goals associated with Titan's origin and evolution can be addressed, Enceladus observations are folded into the considerations by which the mission was assessed.

The results of the ranking are shown in the **Table 2.3-4** as indicating a very high level of fulfillment of the Decadal Survey Large Satellite goals for Titan by the Baseline TSSM mission. The TSSM Floor mission is an orbiter only and defines the science floor. It receives a lower score than the Baseline mission, obviously, since there is no contribution from the experiments to be done *in situ* by the montgolfière and lake lander. Even so, the orbiter-only mission receives a score indicating it is very responsive to the decadal goals, with all but three of the eighteen key questions addressed at a level of "3" or higher.

Each of its instruments on the orbiter addresses multiple scientific objectives and was carefully chosen to avoid duplication with each other while maximizing the complementarity of the data. Thus, an imaging radar would get images at resolution poorer than the HiRIS experiment, but a radar altimeter/sounder compliments both the High Resolution Imager and Spectrometer (HiRIS) images and acquires the topographic and subsurface-structure data that Cassini could not acquire or provided very little of. The JSDT considered removing each instrument, in turn, and found that an acceptable level of scientific return would not be achieved if any of them were removed. Thus, beyond the point of removing the *in situ* elements and their instruments, there is no graceful degradation of the scientific return.

Conversely, in the absence of the *in situ* payload one could add additional instruments to the orbiter payload or make the planning payload instruments larger and more complex. Such a strategy would not yield a science gain equivalent to putting the *in situ* back in place, would add complexity in operating and returning the data from increasing numbers of instruments, and, in fact, beyond a point not too far from the present orbiter payload it would be impossible to map the entire surface with the primary instruments and return the data within the nominal mission lifetime, based on a quantitative simulation of the orbiter mission. In other words, the orbiter begins to suffer from the law of diminishing returns with the addition of more and more instruments. There is only limited freedom in considering additional instruments to the planning payload described here (e.g., a camera for wide-field imaging of Titan on orbit, etc.), but these will add secondarily to the science and NASA must be careful not to create a payload that cannot complete the primary function of mapping the entire globe of Titan and interrogating its atmosphere in many different locations.

An orbiter plus lake lander and montgolfière *is* the Baseline mission because the nature of the Titan environment calls for direct sampling of the surface (lake lander), a mobile platform with surface proximity for very high resolution remote sensing and surface profiling, presence in the atmosphere for detailed wind and meteorology, and deployment of multiple assets (on lander, montgolfière, and the latter's heat shield) below the ionosphere for mapping of the magnetic field—while at the same time using the power of an orbiter to finally map in multiple ways the *entire* surface

Table 2.3-4. *Large satellites panel themes and key questions from the 2003 National Research Council (NRC) Decadal Survey.*

	Orbiter Only	Orbiter + Lander + Montgolfière	Comments
Theme 1. Origin and Evolution of Satellite Systems			
1. How do conditions in the protoplanetary nebula influence the compositions, orbits, and sizes of the resulting satellites?	3	4	
2. What affects differentiation, outgassing, and the formation of a thick atmosphere? (Why is Titan unique?)	3	5	
3. To what extent are the surfaces of icy satellites coupled to their interiors (chemically and physically)?	4	5	
4. How has the impactor population in the outer solar system evolved through time, and how is it different from the inner solar system?	4	4	Enceladus
5. What does the magnetic field of Ganymede tell us about its thermal evolution, and do other large satellites have intrinsic magnetic fields?	1	3	Comparison of magnetic fields between Ganymede and Titan
Theme 2. Origin and Evolution of Water-Rich Environments			
1. What is the chemical composition of the water-rich phase?	3	4	Enceladus plumes and Titan
2. What is the distribution of internal water in space and in time?	3	4	Both Titan and Enceladus
3. What combination of size, energy sources, composition, and history produce long-lived internal oceans?	3	5	Outstanding pairing of large and small body both with potential internal liquid layers, in the same (Saturn) system.
4. Can and does life exist in the internal ocean of an icy satellite?	2	3	Titan isotopic ratios major gases, and Enceladus plume material
Theme 3. Exploring Organic-Rich Environments			
1. What are the chemistry, distribution, and cycling of organic materials on Titan?	3	4	
2. Is Titan internally active, producing water-rich environments with potential habitability?	3	4	
3. What are the current state and history of Titan's surface?	4	5	
4. What drives the meteorology of Titan?	3	5	Combines seasonal coverage with Voyager and Cassini
5. Has there been climate change on Titan?	3	4	
6. Could Titan support life forms that do not require liquid water?	1	5	
Theme 4. Understanding Dynamic Planetary Processes			
1. What are the active interior processes and their relations to tidal heating, heat flow, and global patterns of volcanism and tectonism?	4	5	Enceladus and Titan
2. What are the currently active endogenic geologic processes (volcanism, tectonism, diapirism) and what can we learn about such processes in general from these active worlds?	4	5	Enceladus and Titan
3. What are the complex processes and interactions on the surfaces and in volcanic or geyser-like plumes, atmospheres, exospheres, and magnetospheres?	4	5	Enceladus and Titan
Average Science Value Score			
	3.1	4.4	

Science Value Scoring Key

5	4	3	2	1
Definitely addresses full science	May address full science	Definitely addresses partial	May address partial science	Touches slightly on science

Table 2.3-5. *Traceability from the 2003 National Research Council (NRC) Decadal Survey questions through key discoveries made by Cassini-Huygens to measurements that TSSM would do—unachievable by Cassini.*

Decadal Survey p. 138	Cassini	TSSM
What are the chemistry, distribution and cycling of organic materials on Titan?	Methane/ethane sensed at Huygens site; high altitude polymers; lakes, fluvial	High molecular weight mass spectroscopy; hi-res imaging at 5 µm; near-IR spectra
Is Titan internally active, producing water-rich environments with potential habitability?	Spin rate evidence for ocean; radar images of cryovolcanic features; near-IR spectra of carbon dioxide patches	Accelerometry-enhanced gravity; hi-res surface imaging; surface temperature monitoring in thermal IR; 5–6 µm spectra
What are the current state and the history of Titan's surface?	Radar and VIMS show dearth of craters; fluvial transport at Huygens site	High resolution imaging; radar altimetry and sounding; near-IR spectra
What drives the meteorology of Titan?	Huygens wind and CIRS temperature data provide crude basis for GCM	Sub-millimeter wind/thermal mapping; IR mapping; near-IR cloud sounding
Has there been climate change on Titan?	Fluvial erosion at desert Huygens site; extensive dunes; missing ethane	High resolution imaging; radar sounding; near-IR spectra
Could Titan support life forms that do not require liquid water?	High latitude lakes found, as well as environments where active fluvial flow may occur, and cryovolcanism	Hi-res spectra over 5–6 µm; repeat surface coverage; high molecular weight sampling of upper atmosphere organics

and atmosphere of this variegated world. But it must be emphasized again that *an orbiter-only mission with just the instruments specified here provides a qualitatively different and quantitatively more powerful data set about Titan than did Cassini-Huygens, and will fundamentally revolutionize our understanding of Titan. It will do likewise for Enceladus. The orbiter-only mission is well worth the price of a Flagship.* Given that the orbiter-only mission meets this threshold it must be emphasized that to do nothing because one cannot do everything is to miss an enormous opportunity to address the vast majority of questions listed in §2.3.2. Because of the breadth of science available at Titan, from the massive and dynamic atmosphere to the complex surface and interior, an orbiter mission will provide a wealth of results unparalleled in the outer solar system, more comparable perhaps to an orbiter mission around Mars or Venus.

The analysis makes clear that there is a strong coupling between the Decadal goals, the discoveries made by Cassini-Huygens, and the TSSM objectives. This coupling is illustrated in **Table 2.3-5** for the "Exploring organic-rich environments" theme. The table is constructed by listing the questions from the Decadal Survey in that theme area. For each question, the key discoveries made by Cassini are then given, followed in the final column by the measurements that TSSM would do—unachievable by Cassini—to pursue the answers to the questions in column one now refined and made more detailed by Cassini's accomplishments in column two.

A subsequent report published by the National Academy of Science in 2007 examined the value of Titan and Enceladus as targets for seeking exotic as well as known forms of organic life, in light of the results of the Cassini-Huygens mission. The conclusion of the study committee was that Titan is of very high interest for understanding whether life is a common outcome of chemical reactivity in natural environments, in particular:

> *"Thus the environment of Titan meets the absolute requirements for life. Titan is not at thermodynamic equilibrium. It has abundant carbon-containing molecules and hetero-atoms and a fluid environment. Titan's temperature is low enough to permit a wide range of bonding, covalent and non-covalent. Titan undoubtedly offers other resources believed to be useful for catalysis necessary for life, including metals and surfaces. This makes inescapable the conclusion that if life is an intrinsic property of chemical reactivity, life should exist on Titan." (p. 74)*

The committee went on to conclude:

> *"The stay of the Cassini-Huygens mission on the surface of Titan was brief, but this moon of Saturn is the locale that is most likely to support exotic life. The committee*

believes that it is important to consider whether the planned missions to the solar system should be reordered to permit returning to Titan earlier than now scheduled." (p. 78).

Solar System 2006 roadmap: The 2006 Solar System Roadmap was convened by NASA to consider how solar system exploration could help drive the goals of the NASA Exploration Initiative formulated in 2004, whose principal feature was a return of piloted missions to the Moon and eventually extension to Mars. The roadmap was one of a series worked in parallel by different committees corresponding to the different areas of activity within the agency. As such, the purpose of the committee was not to redefine or reshape the recommendations of the 2003 Decadal Survey, but to use them as a basis for formulating how specific missions would fit into NASA's plan in terms of timing, cost, and impact on the Exploration Program. Thus, the Roadmap Committee adopted the order of outer solar system missions recommended by the Decadal Survey, having available at the time of its deliberations only preliminary results from Cassini-Huygens. The Roadmap Committee did not have at its disposal some of the most exciting results to have come from the Cassini orbiter from 2006–2008 (e.g., the discovery on Titan of northern hemisphere lakes and confirmation of ethane in the southern hemisphere Ontario Lacus; the detection of Titan's asynchronous spin indicating a subsurface liquid layer). Nor did it have the conclusions of the Limits of Organic Life report from the National Academies.

The result of the Roadmap activity was a report confirming the importance of Titan exploration after Cassini-Huygens, and updating the nature of such exploration by orbiter and *in situ* payloads. A new feature of the Roadmap was its endorsement of the use of an aerial vehicle, and specifically a balloon, as the mobility-enabling technology of choice in covering large areas of Titan's surface at high resolution and with direct atmospheric sampling (**Figure 2.3-2**). Because the Roadmap report was not intended to be a review or extension of the science cases developed in the Decadal Survey, the significance of the report lies instead in paving the way for the SDT-1 study, which began immediately after release of the Roadmap. It must be reiterated, however, that many Cassini discoveries of significance with respect to Titan and Enceladus happened after the committee deliberations that produced the report, and so in many respects the Roadmap is out of date with respect to the scientific objectives that motivate Titan exploration—even though less than two years old. Indeed the same may even be said for the report of the SDT-1.

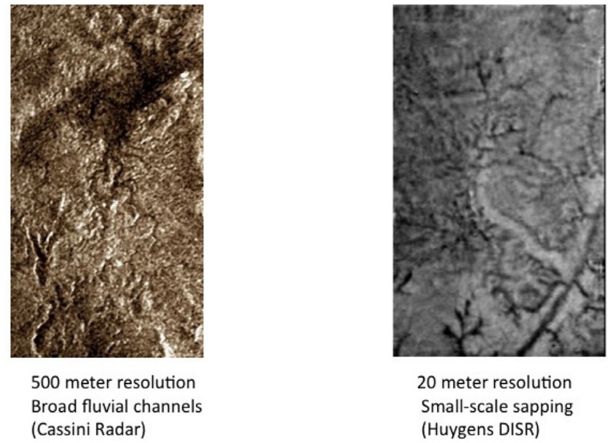


***Figure 2.3-2.** Cassini coverage at large scales at 350–500 m resolutions shows areas of fluvial erosion but not the details of its style (left). The Huygens probe has revealed, at 10–20 m resolution, both dendritic-type fluvial erosion and what appears to be sapping of "ground-methane" (right).*

The goals and objectives laid out here, in contrast, are based on all the results of the Cassini-Huygens Prime Mission that concluded July 1, 2008, as well as the latest guiding recommendations from the National Academy that emphasize the importance of Titan and Enceladus in terms of the potential for life or complex organic chemistry leading toward life.

The NASA Astrobiology Institute (NAI) Executive Council, in a letter on September 22, 2008 (Appendix M), "reaffirms Titan to be in the list of highest priority astrobiological targets in the solar system." Examining the TSSM mission, the NAI Executive Council states that:

"The mission design provides an excellent match for and even exceeds the measurement

objectives identified for targets of high astrobiological potential." It concludes that "a mission to Titan and the Saturn system [is]...in its highest priority mission category."

As this report went to press NASA had just selected as a new NAI node "Titan as a Prebiotic Chemical System", based at JPL, further affirming the priority attached to the science of Titan (see Award Letter in Appendix M).

2.3.6 Mission Goals and Objectives of TSSM

The mission goals for TSSM break into a series of objectives that organize the science investigations discussed in §2.3.6. The connection between the goals and objectives is described here. For convenience in the later discussions, the objectives are labeled as in the traceability matrix of **Table 2.3-1**.

GOAL A—Titan: an Earthlike System. This goal seeks the information necessary to understand how Titan functions as a world, in the same way that one would ask this question about Venus, Mars, and the Earth. How are the distinctions between Titan and other worlds in the solar systems understandable in the context of the complex interplay of geology, hydrology, meteorology, and aeronomy? Is Titan an analogue for some aspect of the Earth's history, past or future? Why is Titan endowed with an atmosphere when Ganymede—Jupiter's moon virtually identical in size and mass—is not?

To address this goal requires proceeding through the entirety of Titan as a system. At the top of Titan's atmosphere, energy is deposited from the Saturnian magnetosphere, the solar wind and solar UV radiation—how much energy is deposited and what is the importance of the various sources must be quantified (*A-O1*). The sources of oxygen for CO and CO_2 chemistry should be more precisely determined, and in particular whether any sources from within Titan contribute (*A-O2*). Titan's atmosphere is a complex chemical system where species form and dissociate, are transported by dynamics, and vary in time and space in ways that are not yet fully understood (*A-O3*). Our understanding of the atmospheric circulation itself—the source of the transport of chemical species and of solar energy and latent heat—is very incomplete but crucial to an understanding of the atmospheric energy balance and composition (*A-O4*).

Titan's methane cycle includes surface liquids, as revealed by Cassini-Huygens, but the amount of liquid on Titan's surface and in immediate contact with the surface has been only partly inventoried, and needs to be more completely determined (*A-O5*). The amount of liquid on the surface, and reshaping the surface, almost certainly has not been constant with time, thanks to loss by photochemistry and escape and possible resupply from the interior. What the history of methane loss and outgassing is, what are the relative contributions of cryovolcanism, cratering and tectonics through time, and how changes in the climate have shaped Titan's surface are the subject of objective *A-O6*.

While Cassini data very recently have given compelling evidence for an internal liquid layer ("ocean"), it is only assumed that this is mostly water. While a plausible assumption, it is imperative to determine this more directly and constrain, if possible, the composition (*A-O7*). Finally, the evolution of Titan's surface-atmosphere system with time depends crucially on whether the interior partially or fully differentiated, and on the subsequent cooling and thickening of the crust; these remain poorly constrained (*A-O8*).

GOAL B—Titan's Organic Inventory: a Path to Prebiological Molecules. Titan is the only world in the solar system where abiotic organic chemistry is ongoing today both in the atmosphere and on (or in) the surface—a surface protected from excessive particle or UV radiation unlike Europa or Mars, respectively. What is the complexity of Titan's organic chemistry in the atmosphere, within its lakes, on its surface, and in the subsurface water ocean hinted at by Cassini data? How does this inventory differ from known abiotic organic material in meteorites and how might it contribute in a unique way to our understanding of the origin of life in the Solar System?

Addressing this goal requires measurements that quantify the origin, evolution, and composition of the organic molecules in the various parts of Titan. Complex organics in the upper atmosphere were discovered recently by Cassini; their formation and the processes leading

to their deposition on the surface are an important objective (*B-O1*). At the same time, the bulk organic inventory of Titan is not well quantified because the surface composition of organics is poorly known. How have the surface organics been modified over time (*B-O3*)? Since the subsurface might contain a liquid water ocean, there is the possibility of aqueous organic chemistry there, and hence it is of keen interest to determine whether the products of such chemistry have been delivered to the surface and what their composition is (*B-O4*). Finally, whether the starting point of Titan's organic chemistry is pure methane or a mix of organics and carbon dioxide more akin to that in meteorites is a fundamental question (*B-O2*), one that requires for its answer determination of the bulk sources of nitrogen and methane in Titan's interior and how they have been delivered to the surface (*B-O5*).

GOAL C—Enceladus and Saturn's magnetosphere: Clues to Titan's Origin and Evolution. The terms of reference for the present study stipulate that aspects of the Saturn system relevant to understanding Titan be included in the mission design. These are Enceladus, whose interior is exposed to analysis through an active plume-geyser system, and the Saturnian magnetosphere which is a medium of exchange of matter and energy with Titan. Here the objectives divide into exploring those aspects of the Saturnian magnetosphere directly related to Titan, and to exploring the composition of the Enceladus plumes and whether the source region is liquid water (with implications for the sources of heating). What is the exchange of energy and material with the Saturn magnetosphere (*C-O1*), especially in light of the new results suggesting more vigorous methane escape and a connection with material from Enceladus? Is the geyser source on Enceladus water-ice or liquid water, and if the latter, how is it maintained? This requires inferring the crustal and deeper structure of Enceladus (*C-O2*), as well as a determination of the extent, if any, of liquid water (*C-O4*). What kind of complex chemistry occurs in the geyser source? Do the chemistry and isotopic composition of the geyser material suggest that methane was abundant as a primordial carrier of carbon, or manufactured in Enceladus (and, by association, Titan) from carbon dioxide and water in contact with rock? These questions require measuring the isotopic composition of the plume gases, and measuring not only light organics as did Cassini but complex, heavy organics as well (*C-O3*). If these organics suggest a form of biological activity then Enceladus becomes a target in its own right for *in situ* exploration on a future mission (*C-05*).

2.3.7 Justification of the Science Investigations and the Required Measurements

This section describes how the science investigations flow from the objectives of the previous section, and how in turn measurement requirements are derived from the science investigations and knowledge of Titan. From the science investigation column onward the matrices for the orbiter and *in situ* elements diverge. In the science investigations column are 46 distinct entries, and another 88 distinct measurement requirements in the column thereafter. The section briefly justifies each science investigation. However, because substantial space is required to explain how each measurement requirement was derived, it is impractical to be comprehensive, even for the orbiter alone. All the measurement requirements were developed by the JSDT drawing on its expertise in a broad range of measurement techniques and observations. Extensive discussion in plenary, in subgroups and by telephone led to the very detailed and extensive list of measurement requirements and approaches appropriate for satisfying them (§2.4 and **Tables 2.3-1**, **2.3-2**, and **2.3-3**).

In this section, then, only selected measurement requirements are elaborated so as to provide a detailed justification. Because this report is by the NASA Ground Rules intended to focus on the orbiter instruments, the measurement requirements are highlighted for the orbiter only.

The science investigations are organized by objective, numbered as in the Traceability matrix. Measurement requirements are highlighted and explained for selected investigations.

Goal A

A-O1: The objective requires measurements of the amount of radiation input to Titan's atmosphere from specific sources: magnetospheric and thermal electron and ions, solar ultraviolet and solar extreme ultraviolet radia-

tion (the last being shortward of 1200 Angstroms). It also requires better quantification of the escape flux not only of methane, but of all abundant carbon and nitrogen species, atoms and ions, as well as of hydrogen itself.

Differential energy measurements are required of three key populations in the Titan environment. First, the populations in Titan's ionosphere, namely positive and negative ions, and electrons including ionospheric photoelectrons must be measured. Cassini has found that high mass species are produced in this region, and these are the seeds for aerosols which may move into the lower atmosphere. Second, measurements of the magnetospheric plasma incident on and penetrating Titan's atmosphere and ionosphere are needed to assess the incident particle energy flux and the species (magnetospheric ions and electrons). Third, measurements of escaping plasma are required to assess Titan's atmospheric loss and to assess Titan as a source for the magnetosphere.

Measuring these three populations provides the requirements for any plasma instrument. In the case of ionospheric ion measurements the flow will primarily be from the ram direction (1 to 1.5 km/s), but for ion temperatures ~180 K the sonic Mach number is ~3 for mass 28 ions with angular width ~18° and energy width ~30%. For mass 78, the Mach number is ~5, angular width ~11° and energy width ~20%. The Mach numbers are considerably lower than Cassini (ram speeds ~6 km/s) and hence the detection range must be broader in energy and angle. The energy spectrum of the ionospheric plasma should be measured for ion energies <1 eV. This capability will allow one to measure ion densities, ion winds and ion temperatures within Titan's ionosphere. The plasma instrument also needs to have a capability to separate N_2^+ and $HCNH^+$ ions with a mass resolution in TOF between 10 and 60 and mass range 1–10,000 Da. The energy range for ionospheric measurements is 5 mV (H^+) to 118 V for mass 10,000 Da. Based on Cassini negative spacecraft potentials ~ -1 V are expected and thus pull the positive ions into the plasma instrument. For energy deposition measurements one needs to separate magnetospheric ions composed of water group ions and methane ions and pickup ions composed of methane ions and dinitrogen ions. Other relevant ions are H^+, H_2^+ and ammonia group ions (N^+, NH_4^+, etc.). For these measurements an energy range of 1 eV to 30 keV is required with good energy resolution (~10%). The angular range should ideally be 4 pi but at least the ram directions and the nominal co-rotation direction must be covered (since spacecraft non-rotator maximum coverage is 2 pi steradians). The mass range for the magnetospheric measurements should cover 1–100 Da with mass resolution $M/\Delta M$ ~10 to 60 to separate energy flow for the main ion species noted above. With regard to atmospheric escape the same requirements for the energy deposition measurements also applies. The escape of neutrals and ions from Titan's atmosphere translates to neutral and plasma tori that will surround Saturn and populate the outer magnetosphere centered around Titan's orbital position but can extend into the inner magnetosphere. Water group ions, methane ions and nitrogen ions must be separated from each other in order to understand the composition of the escaping material.

A-O2: Two different science investigations are required to understand the sources of oxygen. The first is to quantify better the exogenic sources of oxygen; Cassini data indicate indirectly that O must come from the magnetosphere (and hence likely Enceladus), rather than meteoritic water, and so measurements of oxygen bearing species with altitude in the upper atmosphere are needed. But oxygen might be derived from the surface, if large amounts of carbon dioxide are available and can be converted into volatile forms (CO) in volcanic or other processes. This seems unlikely but should be investigated via mapping spectroscopy of the surface at sufficient spectral resolution (exceeded 400) over spot sizes that are less than the size of candidate cryoflows, hence hundreds of meters.

A-O3: The distribution of atmospheric constituents is controlled both by chemistry and by global transport. Two different investigations are required to quantify these: one involving measurements of the atmospheric composition over the full range of altitudes from the surface to the orbiter, and the other to quantify the processes that transport constituents globally. For compositional measurements to be useful in models of global transport, the species abundances in a given altitude range must be determined to better than 10%.

A-O4: The atmospheric thermal and dynamic state can be determined through a series of measurements of the temperature profile with a precision in the lower atmosphere of at least 1 K, enough to see the transition (for example) from the convective-to-radiative portion of the atmosphere a few kilometers above the surface, and to detect temperature gradients between large bodies of liquid and the surroundings. Local winds should be measured near the surface to ~0.1 m/s, which is the threshold value for generating waves and somewhat below that for moving dune particles. Because the wind increases with altitude, accuracies of 5 m/s are sufficient in the stratosphere and above. Understanding global wind fields to a vertical resolution of 10 km is sufficient above the troposphere for input to General Circulation Models; sub-km accuracy in the lower atmosphere (which will require an *in situ* vehicle) is desirable.

The effects of topography on Titan's lower atmospheric weather might be substantial, and show correlating meteorological measurements with topography is essential. For regional scale circulation problems having topography from altimetry to ~10 m vertical and 10 km footprint size is sufficient and allows for global coverage. Determination of the presence of active volcanism through imaging and infrared detection would allow assessment of whether some transient phenomena seen in Cassini data are likely volcanic (or geysering) versus meteorological.

The vertical distributions of the abundances of minor species that act as circulation tracers or participate in the atmospheric energy balance also must be quantified, where possible to 10% accuracy in the mixing ratio.

A-O5: Determination of the amount of liquid on the surface of Titan today means measuring the ethane-methane ratio present in the lakes and seas, principally in the northern hemisphere where more basins seem to be present. The low loss tangent in liquid hydrocarbons of radio waves, and the large size scale of some of the seas, makes remote bathymetry possible. Over spatial scales of 10 km, 10 m depth resolution is useful in determining lake volumes. Near-infrared imaging at selected wavelengths between 2 and 6 μm can, with resolving power of 500, distinguish between ethane and methane in the lakes, thereby determining how much of the lake is potentially mobile with the change of seasons (methane), and available for affecting atmospheric humidity.

A-O6: The history of the surface through time requires understanding the nature and origin of the many enigmatic and varied features on Titan's surface, as well as obtaining a good global topographic map that has proved so revealing of the geology of other surface in the solar system. These are obtained by acquiring imaging and altimetry data along with compositional maps that can be correlated with the geology. The measurement requirements here are three–fold. First, to characterize surface topography with 10 m depth resolution with a resolution of 5–10 km cross track, 1 km lateral (along track) with 10 m vertical precision altimetry. Such topography will aid in understanding geological processes shaping Titan's surface: large near-equatorial basins and highlands, erosional features such as channels, dentritic valley networks, fluvial erosional deltas, and possible glacial-flow features, volcano-tectonic features such as domes, cryovolcanic flows, and bright spots (e.g., Tui Regio, Hotei Regio), slope and roughness of impact craters and other subcircular features, topography, slope and roughness of depressions where former lakes may have been present. Second, assess surface composition with at least an order of magnitude better resolution than was done with VIMS (the usual planetary rule of thumb) (300 m) resolution. Combined with this, imaging data that reveals surface morphology at an order of magnitude better resolution that was available from Cassini radar is required (again a standard rule from one mission to another to balance need for more resolution against problems of data storage and transmission), to reveal the extent of fluvial erosion on the surface, details of cryo-lavas, lake shores, nature of the mountains etc.

A-O7: Exploration of the properties of a subsurface ocean requires the determination of the crustal structure and thickness, and the electrical conductivity of the ocean to assess whether it is salt water. To obtain the crustal structure beneath the surface requires long-wavelength sounding profiles of subsurface dielectric horizons, over the entire mappable surface, up to 5 km depth at 10 m vertical

resolution. The inference that the crust is decoupled from the deep interior by an ocean should be tested through determination of the gravity coefficients of degree-two (J_2, C_{22}, S_{22}) to yield k_2 and phase lag, as well as harmonic amplitudes down to 0.1 ppm Titan surface gravity (equivalent to 1.3×10^{-5} cm/s^2). Extension of the Cassini baseline on the asynchronous rotation of Titan requires imaging measurements that yield rotational parameters to 0.1 degree/yr and pole position shift to 0.1 degree/year.

Sensitive magnetometry from the surface and/or from an orbiter that dips below the ionospheric peak should look for induced magnetic fields associated with a salty ocean below the crust. This requires measuring the vector magnetic field perturbations of order a few nT (with a resolution of order 0.04 nT). The fields are small but well within the capabilities of state-of-the-art Magnetometry.

A-O8. The interior structure of Titan is addressed by gravitational and magnetic measurements. The determination of the global gravity field to at least degree six, will require Doppler accuracy to 50 μm/s over 60 s integration periods. Correlation of topography with gravity is very much in the time-honored tradition of terrestrial planet geophysics. Part of this is the determination of the ratio of geoid harmonics to corresponding gravity harmonics (usually referred to as the "geoid to topography ratio"). The variation of this with harmonic degree conveys information about the internal structure. This information does not have a unique interpretation, typically, but can be modeled in terms of lithospheric thickness or convection, the density of near surface material, the thickness of the layer that does not relax on geologic timescales, and possible presence of uncompensated gravity from a putative rocky core. There is the possibility of seeing the uncompensated gravity of large lakes (if they are partly uncompensated because they fill and empty on seasonal timescale). There is no sharply defined "largest harmonic degree" for the value of this kind of analysis but degree 6 is a good goal.

To seek an internal dynamo requires measuring vector magnetic field perturbations. While *in situ* magnetometry is most sensitive an orbiter that measures fields both above and below the ionospheric peak on an eccentric orbit (for example, during aerobraking) can do a more sensitive search than did Cassini. The sensitivity number is that given for *A-O7*.

Goal B

The objective of understanding the formation of complex organics in the atmosphere and on the surface of Titan is a broad one which requires understanding how species are formed in the high atmosphere, and in particular the complex polymers, determining the sources of energy for atmospheric chemistry and understanding how the aerosols form. A number of measurements are required, some of which are identical to compositional and energetic measurements in Goal A, and listed in the traceability matrix. A particular highlight is the need to sample polymers that range upward from 100 Daltons. The end point is not known and so being able to detect macromolecules with molecular mass of 10,000 Da (hundreds of carbon atoms) is required. At the same time, formation pathways are often constrained through the variation in isotopic ratios of the carbon and nitrogen in the reactants and products; this has been found already for photochemical products in Titan's atmosphere. Therefore, separating masses, with high resolution, in order to make definitive identification of molecular species and isotopic determinations is a vitally important measurement requirement. In addition, measuring the trace gases in Titan's atmosphere of nitrogen and methane requires an instrument that is capable of a large dynamic range (10^8).

B-O2 and *B-O3:* The extent to which the surface organic inventory of Titan differs from the atmospheric and from material exuded from the interior requires spatially resolved measurements of organics at sites where activity such as cryovolcanism might have brought material up from the interior.

The chemical modification at the surface of organics from the atmosphere and from the interior is at the heart of the question of prebiotic chemistry on Titan. It is necessary to quantify the energy sources available for such chemistry, including cosmic rays that reach the surface, cryovolcanism, presence of acetylene that could polymerize and release energy, and impacts. At impact and potential cryovolcanic sites careful analysis (by remote sensing or *in situ*) of organics must be made to determine

whether they differ from that sedimented out of the atmosphere. The reactivity and products of reactions of organic compounds is affecting by doping agents that are usually metals, salts or a variety of minerals. How much of these are on the surface? What happens to the bulk of the aerosols that fall onto the surface? Do they form dune material, coat ice, or get reprocessed by geologic activity? These science investigations require a suite of multidisciplinary measurements, from radar sounding of cryovolanic and impact structures to understand whether the ice is porous or filled with organics, to imaging to identify sites that were recently geologically active. Other measurements will provide tracing of fluvial channels where organics might have been transported as sediment in liquid methane, and spectra for identification of organics exposed at the surface in geologically interesting area.

A spectroscopic search for salts and other potentially reactive materials around cryovolcanic and impact sites is also important, and this in turn requires understanding whether the large numbers of circular features seen at low resolution by radar are caused by some form of cryovolcanism. A search for acetylene on the surface is important to determine where it is and whether all of it has converted to benzene or polymeric products. The required spatial and spectral resolutions of the spectra are those cited above for the general surface mapping because these are adequate to distinguish organic and mineral units associated with features interpreted from Cassini data to be cryo lava flows and possible calderas.

B-O4: Evidence of subsurface ocean species at Titan's surface requires spectroscopic searches for ammonia, sulfates, and more complex organics (e.g., CH_3COOH) at candidate cryovolcanic sites and fresh impacts with spatial resolution ~200 m.

B-O5-I1: Key to the origin of methane is whether CO_2 that appears to be present on the surface is an internally-derived, ancient species, which requires measuring the isotopic composition of surface carbon and oxygen species, and comparing with the isotopic composition of the atmospheric species (photochemically produced CO_2). Precisions in the isotope measurements of 0.1 per mil at high altitudes can be accomplished by direct sampling; surface CO_2 will require remote sensing (spectroscopic) determination of isotopic ratios. A search for ammonia on the surface by covering areas near possible vents with near-IR spectrometry and spot sizes of hundreds of meters can test the hypothesis from noble gas data that the atmospheric nitrogen is derived from ammonia. The presence of ammonia has implications for the organic chemistry in the subsurface ocean as well as surface chemistry, where it could help sustain liquid water pockets for ten times longer duration than pure water itself. Ancillary measurements of possible vent regions with imaging and sounding will help establish whether these features are young.

Goal C

C-O1: Study of the Saturnian magentosphere is the other side of the quantification of energy input and species escape discussed in Goal A. Measurements akin to those described there should be done in the Saturnian magnetosphere over a larger volume than that accessible from Titan orbit, indeed throughout the region between Enceladus and Titan to pursue the link between material supplied by Enceladus and delivered to Titan (e.g., oxygen for CO-CO_2 photochemistry), and to trace the sources of energy that impact Titan's atmosphere.

C-O2: Enceladus' small size and high level of activity pose a challenge for understanding satellite thermal evolution in general, including that of Titan. To understand why Enceladus is active and infer its internal structure requires searching for the presence of partial melt pockets, determining the depth to the rock core, and looking for large mass anomalies. These require mapping of the gravitational coefficients J_2, C_{22}, and S_{22} to degree 2. It also requires a subsurface sounding measurement in the active and inactive regions, with penetration of tens of kilometers through ice, vertical resolution of order 100 m and spot sizes of a few kilometers. Testing for polar wander on Enceladus is also important in understanding the thermal history, and requires high resolution imaging to measure asynchroneity in spin and changes in obliquity.

C-O3: The chemistry of Enceladus' plumes is another window into the volatile budget of the Saturnian satellites, alongside Titan's atmosphere. If aqueous chemistry is possible

in the interior then complex prebiotic or even biotic molecules might have formed. Direct sampling of the plume with high sensitivity over a broad mass range will determine the plume composition both for the major species (including isotopes for comparison with Titan), and assess the extent of internal chemistry. The measurement requirements for the direct chemical sampling are the same as for Titan.

C-O4: Understanding the origin of the thermal anomalies requires mapping the surface temperature distribution in the active cracks, map the surface at high (tens of meters) spatial resolution to gauge any changes from Cassini over two decades, obtain crustal profiles down to the plume source region, map the composition of organics deposited by the plumes on the surface to compare with Cassini maps from two decades before, and search for gravity anomalies. At Enceladus spatial resolutions of remote sensing instruments will be set by flyby distances and the performance of instruments designed for use at Titan, but the requirement is for resolutions at least as good as Cassini's to enable a time baseline of two decades (2009–2029) to be established for assessing changes in one of the most dynamic sites in the solar system.

C-O5: Determine whether fracture sites exist where active plumes could be accessed by the spacecraft. This requires meter to 10 meter scale imaging resolution. Identify ancillary sites near the plumes where fresh samples of water-ice might exist. This requires spectra with resolution of hundreds of meters supplemented by crustal sounding.

The measurement approach that satisfies the measurement requirements, and a planning payload capable of conducting the measurements are detailed in §2.4.

Table 2.3-1. Science traceability matrix: orbiter.

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O1:** Determine how energy is deposited in the upper atmosphere to drive the chemistry and the escape rate of major atmospheric constituents.	**I1:** Quantify the deposition of radiation into Titan's atmosphere.	**M1:** Measure properties of thermal-magnetospheric charged particles that deposit energy into Titan's atmosphere such as fluxes, composition and spatial/temporal dependence of electrons and ions. Measure electrons from 0–1 MeV with 20° angular resolution and 30% energy resolution in the upward-looking and downward-looking hemispheres; ions from 0 to 1 MeV with 20° angular resolution and 30% energy resolution in the upward-looking downward-looking hemispheres and with the ability to stare in the ram and corotation directions at low energies (<30 keV). The plasma instrument must be able to separate methane group ions, ammonia group ions and water group ions.	**A1:** Low Energy Plasma and Particles Instrument includes plasma (ion and electron) spectrometers with energy range eV–30keV Energetic particle spectrometers cover the range 10 keV to 1 MeV. These form part of a combined package with dual head vector Magnetometer and Langmuir probe. Plasma instrument will require time resolution better than 60 s in order to resolve 1 atmospheric scale height or better.	MAPP	• Vector magnetic field data to determine pitch angles • Flux of electrons from 0.01 eV to 1 MeV vs energy, direction and time. • Flux of ions from 0.1 eV to 1 MeV vs energy, direction, composition and time. • Ion composition ((H^+,H_2^+) vs (C^+, N^+, O^+) ions) • Ion velocity moments of density, flow velocity and temperature for thermal and supra-thermal populations vs. time. • Thermal electron density and temperature vs. time.	Periapses from 700 km upward during aerosampling and 950 km upwards during main mission. Complete range of local times and latitudes. Downward and upward going hemispheres visible. Knowledge of the orbiter attitude and a rigid boom to house the magnetometer sensors. If onboard plasma moments are required, the magnetic field measured on board (i.e., without on the ground correction due to spacecraft interference) must have sufficient accuracy to provide the required pitch angle accuracy, this puts constraints on the magnetic cleanliness requirements of the orbiter and the boom length.
			M2: Energy input from thermal-magnetospheric sources. Measure thermal electron density and temperature *in situ* and density profiles as a function of altitude from the ionospheric peak to the orbiter. Measure ionospheric ion density, winds and temperatures in top side ionosphere.	**A1:** Langmuir (swept voltage/current) probe as part of combined package with Low Energy Plasma and Particles Instrument, Energetic Particle Spectrometer and dual vector magnetometer. Time resolution better than 60 s to resolve atmospheric scale height.	MAPP	• Flux of electrons from 0 to 1 MeV vs. energy and direction. • Flux of ions from 0 to 1 MeV vs. energy, direction and composition. • Thermal electron density and temperature vs. time. • Vector magnetic field data to determine pitch angles	Periapses from 700 km upward during aerosampling and 950 km upwards during main mission. Complete range of local times and latitudes.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. *Science traceability matrix: orbiter, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O1:** Determine how energy is deposited in the upper atmosphere to drive the chemistry and the escape rate of major atmospheric constituents.	**I1:** Quantify the deposition of radiation into Titan's atmosphere.	**M3:** Energy input from EUV and UV as a function of altitude from the ionospheric peak to the orbiter.	**A1:** Modeled from swept voltage/current obtained by Langmuir probe.	MAPP	• Thermal electron density and temperature vs. time. • UV flux derived from LP vs. time	Periapses from 700 km upward during aerosampling and 950 km upwards during main mission.
		I2: Quantify the escape flux of elemental hydrogen, carbon, nitrogen.	**M1:** Vertical profiles of atmospheric constituents containing H, C, and N, including major isotopologues, from 800 to 2000 km altitude with precision of better than 5%.	**A1:** Direct sampling Mass spectrometry up to 10,000 Da with sensitivity of less than 10^4 cm^{-3} and dynamic range of 10^8.	PMS	High and low data volume survey mode requires 2 seconds to complete and includes: 1. Open source positive ion spectrum 2. Open source negative ion spectrum 3. Open source neutral spectrum 4. Closed source neutral spectrum 5. High mass resolution mode	Periapses varying from 700 km upward during aerosampling. Ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination. High Data Volume Data Rate: 48 kbits/s.
				A2: Submillimeter sounding at 540–640 GHz with resolution 300 khz and 5% precision in retrieved abundances.	SMS	Alt/lat/local time abundance profiles	Limb viewing from polar orbit, in-track and off-track orientation
			M2: Vertical profiles of atmospheric constituents containing H, C, and N, including major isotopologues, from 100 to 500 km altitude with precision of better than 1%.	**A1:** Passive Thermal-infrared Fourier Transform spectrometry, in the 30–1400 wavenumbers (7–333 µm) region; resolution 0.1–3.0 wavenumber.	TIRS	Thermal and compositional maps and profiles of the stratosphere (50–450 km) with altitude and latitude, HCN (30–720 cm^{-1}), C_2H_6 out to 1400 cm^{-1}, many others	Limb and nadir viewing on polar orbit, in-track and off-track orientation
			M3: Magnetic field of Titan where escape mechanisms of C, N, H are operating. Measure vector magnetic field perturbations of order a few nT (with a resolution of order 0.04 nT) to quantify the escape flux of elemental hydrogen, carbon, and nitrogen	**A1:** Vector Magnetometry (part of a combined instrument).	MAPP	Magnetic field vector at 1 s resolution from both sensors Ion and electron thermal and suprathermal velocity moments of density, temperature, and magnetosphere-ionosphere winds.	Continuous measurements, globally distributed at varying altitudes.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. Science traceability matrix: orbiter, cont'd.

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O2:** Characterize the relative importance of exogenic and endogenic oxygen sources.	**I1:** Quantify the flux of exospheric oxygen into the atmosphere.	**M1:** Vertical profiles atmospheric constituents containing oxygen including major isotopologues, from 100–1500 km altitude with precision better than 5%.	**A1:** Submillimeter sounding at 540–640 GHz with resolution 300 khz and 5% precision in retrieved abundances.	SMS	Alt/lat/local time abundance profiles	Limb viewing from polar orbit, in-track and off-track orientation
				A2: Direct sampling Mass spectrometry up to 10,000 Da at 1% peak height with mass resolution 3000–10,000 and high sensitivity (0.1 ppm at 850 km).	PMS	High and low data volume survey mode requires 1 second to complete and includes: 1. Open source positive ion spectrum 2. Open source negative ion spectrum 3. Open source neutral spectrum 4. Closed source neutral spectrum High Data Volume Data Rate: 48 kbits/s	Periapses varying from 700 km upward and ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination. Low Data Volume Data Rate: 4 kbits/s
			M2: Vertical profiles of atmospheric constituents containing oxygen including major isotopologues, in lower atmosphere with precision of 1%.	**A1:** Passive Thermal-infrared Fourier Transform spectrometry, in the 30–1400 wavenumbers (7–333 μm) region (CO at 30–80 cm^{-1}, H_2O at 60–200 cm^{-1}, CO_2 at 670 cm^{-1}) resolution 0.1–3.0 wavenumber.	TIRS	Thermal and compositional maps and profiles of the stratosphere (50–450 km) with altitude and latitude.	Limb and nadir viewing on polar orbit, rotation in azimuth
		I2: Quantify the flux of endogenic oxygen from the surface and interior.	**M1:** Inventory of surface constituents containing oxygen including major isotopologues at 250 m resolution.	**A1:** Near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 μm and 4.8–5.8 μm with spectral resolution >400 and spatial resolution = 250 m.	HiRIS	Near-IR spectral cubes characterizing the surface of Titan at 250 m resolution	Prefer mapping phase orbit within ±3 hrs from local noon

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. *Science traceability matrix: orbiter, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O3:** Characterize the major processes controlling the global distribution of atmospheric chemical constituents.	**I1:** Characterize the major chemical cycles.	**M1:** Vertical, latitudinal and temporal dependence of condensed and gaseous species in the atmosphere from the surface to 1500 km with precision better than 10%.	**A1:** Passive Thermal-infrared Fourier Transform spectrometry, in the 30–1400 wavenumbers (7–333 μm) region; resolution 0.1–3.0 wavenumber.	TIRS	Thermal and compositional maps and profiles of the stratosphere (50–450 km) with altitude and latitude	Limb and nadir viewing on polar orbit, rotation in azimuth
				A2: Submillimeter sounding at 540–640 GHz with resolution 300 khz and 10% precision in retrieved abundances.	SMS	Alt/lat/local time abundance profiles	Limb viewing on polar orbit, rotation in azimuth
				A3: Direct sampling Mass spectrometry up to 10,000 Da with mass resolution 3000–10,000 at 1% peak height, high sensitivity (0.1 ppm at 850 km) and a dynamic range of 10^8.	PMS	High and low data volume survey mode require 2 seconds to complete and includes: 1. Open source positive ion spectrum 2. Open source negative ion spectrum 3. Open source neutral spectrum 4. Closed source neutral spectrum 5. High mass resolution mode High Data Volume Data Rate: 48 kbits/s	Periapses varying from 700 km upward and ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination.
		I2: Determine the relative importance of global transport.	**M1:** 4D transport with precision of better than 5%.	**A1:** Mid- to far-infrared spectra of the stratosphere in the 30–1400 wavenumbers (7–333 μm) region, spectral resolution of 3 to 15 wavenumbers, spatial resolution of <5 mrad IFOV.	TIRS	Thermal and compositional maps and profiles of the stratosphere (50–450 km) with altitude and latitude.	Limb and nadir viewing on polar orbit, rotation in azimuth
				A2: Submillimeter sounding at 540–640 GHz with resolution 300 khz and 10% precision in retrieved abundances and 5 m/s in winds.	SMS	Alt/lat abundance and wind profiles	Limb viewing from polar orbit, in-track and off-track orientation

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. Science traceability matrix: orbiter, cont'd.

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O3:** Characterize the major processes controlling the global distribution of atmospheric chemical constituents.	**I2:** Determine the relative importance of global transport.	**M1:** 4D transport with precision of better than 5%.	**A3:** Direct sampling Mass spectrometry up to 10,000 Da with mass resolution 3000–10,000 at 1% peak height, high sensitivity (0.1 ppm at 850 km) and a dynamic range of 10^8.	PMS	High and low data volume survey mode spectra: 1. Open source positive ion spectrum 2. Open source negative ion spectrum 3. Open source neutral spectrum 4. Closed source neutral spectrum 5. High mass resolution mode High Data Volume Data Rate: 48 kbits/s	Periapses varying from 700 km upward and ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination.
	O4: Characterize the atmospheric circulation and flow of energy and its variability on short-timescales.	**I1:** Determine the atmospheric thermal and dynamical state.	**M1:** Temperature versus pressure for altitude, lat/long, and time. Stratospheric temperature to 1 K and tropospheric / mesospheric temperatures to 0.1 K; pressure to 10%. Vertical resolution < scale height thermosphere and stratosphere; 0.5 km troposphere.	**A1:** Mid- to far-infrared spectra of the stratosphere in the 30–1400 wavenumbers (7–333 μm) region, spectral resolution of 3 to 15 wavenumbers, spatial resolution of <5 mrad IFOV.	TIRS	Thermal and compositional maps and profiles of the stratosphere (50–450 km) with altitude and latitude	Limb and nadir viewing on polar orbit, rotation in azimuth
				A2: Radio occultations over latitudes 85°N to 85°S using the USO. End to end radio link stability (Allan deviation) required to carry out the measurement is 10^{-13} at 10 s integration time.	RSA	Temperature-pressure profile vs. altitude	Optimized occultation geometry
				A3: Submillimeter sounding at 540–640 GHz with resolution 300 khz and 1 K accuracy in retrieved atmospheric temperatures.	SMS	Alt/lat/local time temp. profiles	Limb viewing on polar orbit, rotation in azimuth

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. *Science traceability matrix: orbiter, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy and its variability on short-timescales.	**I1:** Determine the atmospheric thermal and dynamical state.	**M2:** Winds with ~5 m/s or better accuracy. Zonal and meridional. Global 3D wind and temperature fields from 100 to 1500 km at vertical resolution of 10 km.	**A1:** Image clouds using a low spatial and spectral resolution mode of the near-IR spectrometer that provides images in multiple near-IR wavelengths, both in and out of the methane windows, 130 km wide with 1 km resolution during the circular mapping phase, and 1000 km wide with 2 km resolution during aerobraking.	HiRIS	Maps of the regional distribution of clouds in Titan's atmosphere with 1–2 km resolution providing for several Earth years of temporal coverage	Requires observations during Saturn orbit and aerosampling (elliptical orbit) phase
				A2: Mid- to far-infrared spectra of the stratosphere in the 30–1400 wavenumbers (7–333 μm) region, spectral resolution of 3 to 15 wavenumbers, spatial resolution of <5 mrad IFOV.	TIRS	Thermal and compositional maps and profiles of the stratosphere (50–450 km) with altitude and latitude	Limb and nadir viewing on polar orbit, rotation in azimuth
				A3: Submillimeter at 540–640 GHz with resolution 300 khz down and 5 m/s accuracy in retrieved zonal and meridional winds.	SMS	Alt/lat profiles of zonal and meridional winds	Limb viewing from polar orbit, in-track and off-track orientation
		I2: Determine the impact of haze and clouds.	**M1:** Cloud frequency with a spatial resolution of1 km and fields of view >hundreds of kilometers in extent.	**A1:** Image clouds using a low spatial and spectral resolution mode of the near-IR spectrometer that provides images in multiple near-IR wavelengths, both in and out of the methane windows, 130 km wide with 1 km resolution during the circular mapping phase, and 1000 km wide with 2 km resolution during aerobraking.	HiRIS	Maps of the regional distribution of clouds in Titan's atmosphere with 1–2 km resolution providing for several Earth years of temporal coverage	Requires observations during Saturn orbit and aerosampling (elliptical orbit) phase

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. *Science traceability matrix: orbiter, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy and its variability on short-timescales.	**I2:** Determine the impact of haze and clouds.	**M2:** Cloud top altitude and vertical extent, morphology, size of clouds and likelihood of precipitation. Resolve heights to 10% of a scale height; determine cloud bases through direct or indirect (e.g., methane vapor profile) approaches. Repeat observations of early summer hemisphere convective clouds at spatial resolution 1 km.	**A1:** Image clouds using a low spatial and spectral resolution mode of the near-IR spectrometer that provides images in multiple near-IR wavelengths, both in and out of the methane windows, 130 km wide with 1 km resolution during the circular mapping phase, and 1000 km wide with 2 km resolution during aerobraking.	HiRIS	Maps of the regional distribution of clouds in Titan's atmosphere with 1–2 km resolution providing for several Earth years of temporal coverage	Repeat passes over high southern latitudes during mapping phase.
		I3: Determine the effects of atmospheric composition.	**M1:** Vertical distributions of abundances of minor constituents as a function of latitude, time of day and season with better than 10% accuracy.	**A1:** Mid-infrared spectra of the stratosphere in the 30–1400 wavenumbers (7–333 μm) region, spectral resolution of 0.1–3 wavenumbers, spatial resolution of <5 mrad IFOV.	TIRS	Thermal and compositional maps and profiles of the stratosphere (50–450 km) with altitude and latitude	Limb and nadir viewing on polar orbit, rotation in azimuth
				A2: Submillimeter sounding at 540–640 GHz with resolution 300 khz and 5% precision in retrieved abundances.	SMS	Alt/lat/local time abundance profiles	Limb viewing from polar orbit, in-track and off-track orientation
				A3: Direct sampling Mass spectrometry up to 10,000 Da at 1% peak height with mass resolution 3000–10,000 and a dynamic range of 10^8.	PMS	High and low data volume survey mode requires 1 s to complete and includes: 1. Open source positive ion spectrum 2. Open source negative ion spectrum 3. Open source neutral spectrum 4. Closed source neutral spectrum High Data Volume Data Rate: 48 kbits/s Low Data Volume Data Rate: 4 kbits/s	Periapses varying from 700 km upward during aerosampling. Ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. Science traceability matrix: orbiter, cont'd.

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy and its variability on short-timescales.	**I4:** Determine the effects of surface processes on meteorology.	**M1:** Global topography with 10 m depth resolution in the region from 85°N to 85°S. Horizontal resolution required is 5–10 km cross track, 1 km lateral (along track) with 10 m vertical precision altimetry. Long temporal coverage of active regions.	**A1:** Altimetry measurements with single band (>20 MHz center) radar with capability of ~10 m height resolution and 1 km (along-track) and 5-10 km (cross-track) spatial resolution.	TiPRA	Quasi-global Topography map of Titan's surface with a spatial resolution of 1–10 km and a vertical resolution of ~10 m, repeated coverage of active regions	TiPRA can operate on the nightside.
			M2: Map extent of surface covered by liquid at 50 m resolution and 80% surface coverage.	**A1:** High-resolution near-IR imaging at 2.05 ± 0.08 µm, 2.73 ± 0.08 µm, and 5.35 ± 0.45 µm.	HiRIS	Three-color maps of 80% of Titan's surface at 50 m resolution	Prefer mapping phase orbit at ±4 hrs from local noon
			M3: Temperature gradients between liquid surface and surrounding terrains with 1 K precision.	**A1:** Mid- to far-infrared spectra of the stratosphere from 30–1400 wave numbers (7–333 µm), spectral resolution of 3 to 15 wave numbers, spatial resolution of <5 mrad IFOV.	TIRS	Far-IR thermal property maps of surface	Nadir viewing
			M4: Identify active volcanism in the equatorial region with 50 m resolution from orbit and .2.5 m resolution from 10 km altitude	**A1:** High-resolution near-IR imaging at 2.05 ± 0.08 µm, 2.73 ± 0.08 µm, and 5.35 ± 0.45 µm.	HiRIS	Three-color maps of 80% of Titan's surface at 50 m resolution, contribution to thermal maps of the surface	Prefer mapping phase orbit at ±4 hrs from local noon
				A2: Mid- to far-infrared spectra of the stratosphere from 30–1400 wave numbers (7–333 µm), spectral resolution of 3 to 15 wave numbers, spatial resolution of <5 mrad IFOV.	TIRS	Thermal and compositional maps and profiles of the stratosphere (50–450 km) with altitude and latitude	Limb and nadir viewing on polar orbit, rotation in azimuth
	O5: Characterize the amount of liquid on the Titan surface today.	**I1:** Quantify the total major-hydrocarbon (methane/ethane) inventory present in the lakes and seas.	**M1:** Lake and sea bathymetry. Lateral 10 km /10 m vertical precision.	**A1:** Single band (>20 MHz center) penetrating radar and altimetry with capability of sub-surface sounding to a depth of ~5 km with ~10 m depth resolution.	TiPRA	3D maps of lake and sea regions with a vertical resolution of ~10 m, spatial resolution of ~10 km, to a depth of 5 km	Measurement above the lake early and late in the mapping phase for seasonal progression

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. Science traceability matrix: orbiter, cont'd.

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O5:** Characterize the amount of liquid on the Titan surface today.	**I1:** Quantify the total major-hydrocarbon (methane/ethane) inventory present in the lakes and seas.	**M2:** Map extent of surface covered by liquid at 50 m resolution and 80% surface coverage.	**A1:** High-resolution near-IR imaging at 2.05 ± 0.08 μm, 2.73 ± 0.08 μm, and 5.35 ± 0.45 μm.	HiRIS	Three-color maps of 80% of Titan's surface at 50 m resolution; will enable assessment of drainage into the subsurface and porosity	Prefer mapping phase orbit at ±4 hrs from local noon. Measurement above the lake early and late in the mapping phase for seasonal progression
		I2: Determine the depth of the lake at the landing site.	**M1:** Lake and sea bathymetry. Lateral 10 km /10 m vertical precision.	**A1:** Single band (>20 MHz center) penetrating radar and altimetry with capability of sub-surface sounding to a depth of ~5 km with ~10 m depth resolution.	TiPRA	3D maps of lake and sea regions with a vertical resolution of ~10 m, spatial resolution of ~10 km, to a depth of 5 km	Coordinated effort with lander and orbiter.
	O6: Characterize the major processes transforming the surface throughout time.	**I1:** Determine the origin of major crustal features; correlate regional elevation changes with geomorphology and compositional variations.	**M1:** Surface topography with 10 m height resolution in the region from 85°N to 85°S. Horizontal resolution required is 5–10 km cross track, 1 km lateral (along track) with 10 m vertical precision altimetry. Long temporal coverage of active regions	**A1:** Altimetry measurements with single band (>20 MHz center) radar with capability of ~10 m height resolution and 1 km (along-track) and 5–10 km (cross-track) spatial resolution.	TiPRA	Quasi-global topography map of Titan's surface with a spatial resolution of 1–10 km and a vertical resolution of ~10 m, repeated coverage of active regions	TiPRA can take data on the nightside.
			M2: Surface topography with 10 m height resolution and 0.5 km spatial resolution.	**A1:** High-resolution near-IR stereo imaging at 5.35 ± 0.45 μm.	HiRIS	5 μm stereo maps of 80% of Titan's surface with 10 m height resolution and 0.5 km spatial resolution	Requires two global maps: one acquired near nadir and one acquired looking off nadir
			M3: Surface composition with 250 m resolution in region at all available latitudes	**A1:** Near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 μm and 4.8–5.8 μm with spectral resolution >400 and spatial resolution = 250 m.	HiRIS	Near-IR spectral cubes characterizing the surface of Titan at 250 m resolution	Prefer mapping phase orbit within ±3 hrs from local noon
			M4: Map surface features at 50 m resolution in multiple wavelengths and 80% surface coverage and correlate morphology and spectral characteristics of surface features with topography.	**A1:** High-resolution near-IR imaging at 2.05 ± 0.08 μm, 2.73 ± 0.08 μm, and 5.35 ± 0.45 μm.	HiRIS	Three-color maps of 80% of Titan's surface at 50 m resolution	Prefer mapping phase orbit at ±4 hrs from local noon

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. *Science traceability matrix: orbiter, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O6:** Characterize the major processes transforming the surface throughout time.	**I2:** Characterize the origin of major surface features, including the effects of liquid flow, tectonic, volcanic, and impact events.	**M1:** Map surface features at 50 m resolution in multiple wavelengths and 80% surface coverage and correlate morphology and spectral characteristics of surface features with topography.	**A1:** High-resolution near-IR imaging at 2.05 ± 0.08 µm, 2.73 ± 0.08 µm, and 5.35 ± 0.45 µm.	HiRIS	Three-color maps of 80% of Titan's surface at 50 m resolution	Prefer mapping phase orbit at ±4 hrs from local noon
			M2: Search for surface changes, especially in lakes, channels, volcanic and aeolian features (tectonic changes and impacts are less likely).	**A1:** Repeated high-resolution near-IR imaging of selected regions on several timescales at 2.05 ± 0.08 µm, 2.73 ± 0.08 µm, and/or 5.35 ± 0.45 µm.	HiRIS	Regional maps of active regions of Titan's surface (e.g., polar regions) repeated multiple times during the prime mission	Repeated observations over variety of timescales, especially in regions where changes are likely (e.g., polar regions, sites of clouds/storms/precipitation), prefer mapping phase orbit at ±4 hrs from local noon
		I3: Determine the internal magnetic signal of Titan	**M1:** Magnetic map of the surface	**A1:** Dual sensor, vector magnetometer, with sensors located on a boom away from the magnetic signature of the Orbiter.	MAPP	Normal mode 16Hz data from primary sensor and 1Hz data from secondary sensor, with burst mode of 128Hz data from primary sensor triggered by command or autonomously.(Normal mode 900 bits per second (bps), burst mode 6500 bps	Precise location of the orbiter, Orbiter attitude and rigid boom for the magnetometer sensor. Continuous magnetic field data, as much coverage of the surface as possible. Consider-ation of magnetic cleanliness requirements vs. boom length
		I4: Detect and measure the depth of shallow subsurface reservoirs of liquid (hydrocarbons).	**M1:** Sounding profiles of subsurface dielectric horizons, over the entire mappable surface, up to 5 km depth at 10 m vertical resolution, and long temporal coverage of active regions.	**A1:** Single band (>20 MHz center) penetrating radar with capability of sub-surface sounding to a depth of ~5 km with ~10 m depth resolution.	TiPRA	2D and 3D maps of Titan's subsurface up to 5 km depth, with a vertical resolution of ~10 m, and a spatial resolution of ~10 km; repeated coverage of active regions	TiPRA can take data on the nightside.
	O7: Determine the existence of a subsurface liquid water ocean.	**I1:** Determine crustal/subcrustal structure; reflectance of subsurface stratification.	**M1:** Sounding profiles of subsurface dielectric horizons, over the entire mappable surface, up to 5 km depth at 10 m vertical resolution, and long temporal coverage of active regions.	**A1:** Single band (>20 MHz center) penetrating radar with capability of sub-surface sounding to a depth of ~5 km with ~10 m depth resolution.	TiPRA	2D and 3D maps of Titan's subsurface up to 5 km depth, with a vert-ical resolution of ~10 m, and a spatial resolution of ~10 km; repeated cov-erage of active regions	TiPRA can take data on the nightside.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. Science traceability matrix: orbiter, cont'd.

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O7:** Determine the existence of a subsurface liquid water ocean.	**I2:** Determine if the crust is decoupled from the interior and the thickness and rigidity of the icy crust.	**M1:** Degree-two gravity coefficients (J_2, C_{22}, S_{22}) to yield k_2 and phase lag. Harmonic amplitudes down to 0.1 ppm Titan surface gravity (equivalent to 1.3×10^{-5} cm/s^2).	**A1:** Relative velocity between the spacecraft and ground station determined from Doppler tracking with an accuracy up to 50 µm/s with 60 s integration periods. (Ka-band link stability ~10^{-15} after all calibrations including accelerometer for non-gravitational forces).	RSA	Coefficients of spherical harmonic expansion of gravity field for further analysis and interpretation in terms of internal structure. The static degree-two gravity field will lead to constraints on the global density structure of the interior. Time variations of the degree-two field will lead to investigating the tidal response of the satellite and constraining its visco-elastic structure and crustal thickness	Optimized gravity configuration near closest approach with minimized non-gravitational forces; repeat observations at the same C/A point but different true anomalies (e.g., apoapsis, periapsis)
			M2: Rotation parameters to 0.1 degree/yr and pole position shift to 0.1 degree/year.	**A1:** Repeated high-resolution near-IR imaging at 2.05 ± 0.08 µm, 2.73 ± 0.08 µm, and/or 5.35 ± 0.45 µm.	HiRIS	High-resolution images of a set of fiducial points identified on Titan's surface repeated multiple times during the prime mission	Repeated observations of fiducial points
			M3: The long-wavelength topography of Titan and topographic effects of large-scale geologic structures. Lateral 1–10 km/vertical 10 m; satisfied by global topographic measurements.	**A1:** Altimetry measurements with single band (>20 MHz center) radar with capability of ~10 m height resolution and 1 km (along-track) and 5–10 km (cross-track) spatial resolution.	TiPRA	Quasi-global topography map of Titan's surface with a spatial resolution of 1–10 km and vertical resolution of ~10 m	TiPRA can take data on the nightside. Need to tune the frequency after first pass.
		I3: Determine the induced magnetic field signatures in order to confirm subsurface liquid and place constraints on the conductivity and depth of the liquid	**M1:** Measure vector magnetic field perturbations of order a few nT (with a resolution of order 0.04 nT). Measurements of the inducing magnetic field allow separation of the inducing magnetic field (measured by the orbiter) from the induced fields (measured by the montgolfière/lander).	**A1:** Vector Magnetometry (part of a combined instrument).	MAPP	Continuous magnetic field vectors at 1 s resolution, globally distributed, at varying altitudes	Requires a combination of orbiter and montgolfière magnetometer measurements to be able to unequivocally resolve the induced signatures.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. *Science traceability matrix: orbiter, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O8:** Determine the state of internal differentiation, whether Titan has a metal core and an intrinsic magnetic field, and constrain the crustal expression of thermal evolution of Titan's interior.	**I1:** Map interior structure of Titan.	**M1:** Global gravity field to at least degree six. Doppler accurate to 50 µm/s with 60 s integration periods.	**A1:** Relative velocity between the spacecraft and ground station determined from Doppler tracking with an accuracy up to 50 µm/s with 60 s integration periods. (Ka-band link stability $\sim 10^{-15}$ after all calibrations including accelerometer for non-gravitational forces).	RSA	Coefficients of spherical harmonic expansion of gravity field for further analysis and interpretation in terms of internal structure. The static degree-two gravity field will lead to constraints on the global density structure of the interior. Time variations of the degree-two field will lead to investigating the tidal response of the satellite and constraining its viscoelastic structure and crustal structure.	Prefer mapping phase orbit height of 1500 km
		I2: Determine whether Titan has a dynamo.	**M1:** Detect or set limits on the intrinsic magnetic field of Titan. Measure vector magnetic field perturbations of order a few nT (with a resolution of order 0.04 nT).Thermal and magnetospheric plasma measurements will provide supportive role with regard to external currents from magnetospheric measurements.	**A1:** Vector Magnetometry (part of a combined instrument).	MAPP	Magnetic field vector at 1 s resolution from both sensors Ion and electron thermal and suprathermal velocity moments of density, temperature and magnetosphere-ionosphere winds.	Continuous measurements, globally distributed at varying altitudes. Knowledge of orbiter attitude and location, and a rigid magnetometer boom. Consideration of magnetic cleanliness requirements vs. boom length.
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O1:** Determine the processes leading to form-ation of complex organics in the Titan atmosphere and their deposition on the surface.	**I1:** Assay the speciation and abundances of atmospheric trace molecular constituents.	**M1:** Abundances of monomer and polymer organic species and inorganic species with a detectability of <1 ppb and an accuracy of better than 3% over an altitude range from 30–1500 km.	**A1:** Passive Thermal-infrared Fourier Transform spectrometry, in the region from 30–1400 wavenumbers (7–333 µm); resolution 0.1–3.0 wavenumber.	TIRS	Thermal and compositional maps and profiles of the stratosphere (50–450 km) with altitude and latitude	Limb and nadir viewing on polar orbit, rotation in
				A2: Submillimeter sounding at 540–640 GHz with resolution 300 khz and 10% precision in retrieved abundances.	SMS	Alt/lat maps of selected organics	Limb viewing from polar orbit, in-track and off-track orientation

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. Science traceability matrix: orbiter, cont'd.

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O1:** Determine the processes leading to formation of complex organics in the Titan atmosphere and their deposition on the surface.	**I1:** Assay the speciation and abundances of atmospheric trace molecular constituents.	**M1:** Abundances of monomer and polymer organic species and inorganic species with a detectability of <1 ppb and an accuracy of better than 3% over an altitude range from 30–1500 km.	**A3:** Direct sampling Mass spectrometry up to 10,000 Da with mass resolution 10,000 at 1% of the peak height, sensitivity of 1 ppb at 850 km and a dynamic range of 10^8.	PMS	High and low data volume survey mode spectra: 1. Open source positive ion spectrum 2. Open source negative ion spectrum 3. Open source neutral spectrum 4. Closed source neutral spectrum 5. High mass resolution mode High Data Volume Data Rate: 48 kbits/s	Periapses varying from 700 km upward during aerosampling. Ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination.
			M2: Stable isotope ratios of nitrogen, carbon, oxygen and hydrogen in photochemical products of methane, nitrogen and carbon monoxide.	**A1:** Direct sampling Mass spectrometry up to 10,000 Da with mass resolution 10,000 at 1% of the peak height and a dynamic range of 10^8.	PMS	High and low data volume survey mode spectra: 1. Open source positive ion spectrum 2. Open source negative ion spectrum 3. Open source neutral spectrum 4. Closed source neutral spectrum 5. High mass resolution mode High Data Volume Data Rate: 48 kbits/s	Periapses varying from 700 km upward during aerosampling. Ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination.
		I2: Assay the molecular complexity of the condensed phase.	**M1:** Abundances of organic species in the atmosphere with a detectability of <1 ppb and an accuracy of better than 3% over an altitude range of 30–500 km, at polar latitudes with <5 mradians spatial resolution and long temporal coverage.	**A1:** Passive Thermal-infrared Fourier Transform spectrometry, in the region 30–1400 wavenumbers (7–333 μm); resolution 0.1–3.0 wavenumbers.	TIRS	Thermal and compositional maps and profiles of the stratosphere (50–450 km) with altitude and latitude	Limb and nadir viewing on polar orbit, rotation in azimuth

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. Science traceability matrix: orbiter, cont'd.

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O1:** Determine the processes leading to formation of complex organics in the Titan atmosphere and their deposition on the surface.	**I3:** Quantify the sources of chemical energy for atmospheric chemistry.	**M1:** 3D ion-electron plasma measurements with FOV ~2π steradians, view flow in corotation and ram directions; view upward and downward looking hemispheres (unlikely to be simultaneous at all times). 3D plasma electron measurements must cover the energy range from 1 eV to 30 keV with angular resolution ~ 20°x20°, energy resolution $\Delta E/E$ ~18% and geometric factor GF ~ 1.0e^{-3} cm^2-ster-eV/eV. Electron measure-ments from 0.01 eV to 40 eV will be provided by LP. 3D plasma ion measurements must cover the energy range from 1 eV to 30 kV, angular resolution 20°x20°, energy resolution $\Delta E/E$ ~18%, mass range $1 \leq M/Q \leq 10{,}000$ amu/charge, and geometric factor GF ~ 1.0e^{-3} cm^2-ster-eV/eV .The energetic particle measurements will be from 20 keV to 1 MeV for electrons and 10 MeV for ions with energy resolution $\Delta E/E$ ~30%, angular resolution ~30° and GF ~ 0.05 cm^2-ster or greater. The energetic ion measurements should have mass resolution $M/\Delta M$ ~10 or better.	**A1:** Low Energy Plasma and Particles Instrument (measures ion and electron fluxes from few ev^{-10} MeV. Plasma instrument (E/Q <30 kV) must separate water group, methane group and ammonium group ions with TOF mass resolution $M/\Delta M$ ~10 to 60 Energetic Particle Spectrometer (measures magnetospheric particle fluxes from 10 keV to >Mev) with $M/\Delta M$ ~10 as part of a combined package with dual head vector Magnetometer and Langmuir probe.	MAPP	• Magnetic field vector data for pitch angle determination • Flux of electrons from 0.01 eV to 1 MeV vs energy and direction • Flux of ions from 0.1 eV to 1 MeV vs. energy, direction, ion composition and time. • Ion composition ((H+,H2+) vs C, N, O) ions) • Ion and electron velocity moments of densities, winds and temperatures vs. time. • Thermal electron density and temperature vs. time	Periapses from 700 km upward during aerosampling and 950 km upwards during main mission. Complete range of local times and latitudes. Downward going hemisphere visible.
			M2: Thermal electron density and temperature from ionosphere peak upward.	**A1:** Langmuir (swept voltage/current) probe as part of combined package with Low Energy Plasma and Particles Instrument, Energetic Particle Spectrometer and dual vector magnetometer. (Note: to obtain implied vertical profile requires topside sounding using low frequency ionospheric sounder addition to TiPRA similar to MARSIS])	MAPP	Thermal electron density and temperature vs. time ion densities, ion composition, ion temperature and ion flows vs. time	Atmospheric sampling phase to get vertical profiles.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. *Science traceability matrix: orbiter, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O1:** Determine the processes leading to formation of complex organics in the Titan atmosphere and their deposition on the surface.	**I3:** Quantify the sources of chemical energy for atmospheric chemistry.	**M3:** Flux of UV photons.	**A1:** : Modeled from swept voltage/current obtained by Langmuir probe (part of combined package)	MAPP	Thermal electron density and temperature vs. .time ion densities, ion composition, ion temperature and ion flows vs. time	Continuous measurements, globally distributed at varying altitudes
		I4: Determine surface composition.	**M1:** Inventory organic and inorganic surface constituents at 250 m spatial resolution.	**A1:** Near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 µm and 4.8–5.8 µm with spectral resolution >400 and spatial resolution = 250 m.	HiRIS	Near-IR spectral cubes characterizing the surface of Titan at 250 m resolution	Prefer mapping phase orbit within ±3 hrs from local noon
	O2: Characterize the degree to which the Titan organic inventory is different from known abiotic organic material in meteorites.	**I1:** Assay the composition of organic deposits exposed at the surface, including dunes, lakes, seas.	**M1:** Inventory organic and inorganic surface constituents at 250 m spatial resolution.	**A1:** Near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 µm and 4.8–5.8 µm with spectral resolution >400 and spatial resolution = 250 m.	HiRIS	Near-IR spectral cubes characterizing the surface of Titan at 250 m resolution	Prefer mapping phase orbit within ±3 hrs from local noon
	O3: Characterize what chemical modification of organics occurs on the surface.	**I1:** Determine the roles of cratering and cryovolcanism in modification and hydrolysis of organics.	**M1:** Inventory organic species between +65 and -90 degrees latitude with 250 m spatial resolution and long temporal coverage.	**A1:** Repeated near-IR mapping spectroscopy within the 2- and 5-µm atmospheric-methane transmission windows (1.9–2.4 µm and 4.8–5.8 µm) with spectral resolu-tion >400 and spatial resolution = 250 m.	HiRIS	Near-IR spectral cubes of selected regions of Titan at 250 m resolution repeated multiple times during the prime mission	Prefer mapping phase orbit within ±3 hrs from local noon
			M2: Sounding profiles of subsurface dielectric horizons with 10 m vertical resolution and extensive surface coverage. Horizontal resolution required is 5–10 km cross track, 1 km lateral (along track) with 10 m vertical precision altimetry.	**A1:** Single band (>20 MHz center) penetrating radar with capability of sub-surface sounding to a depth of ~5 km with ~10 m depth resolution.	TiPRA	2D and 3D maps of Titan's subsurface up to 5 km depth, with a vertical resolution of ~10 m, and a spatial resolution of ~10 km	
		I2: Determine the importance of surface inorganic compounds as surface catalysts or doping agents.	**M1:** Identify inorganic salts and compounds containing phosphorous and other potentially reactive inorganic agents, from latitude 85°N to 85°S with 250 m spatial resolution and long temporal coverage.	**A1:** Partially completed with repeated near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 µm and 4.8–5.8 µm with spectral resolution >400 and spatial resolution = 250 m.	HiRIS	Near-IR spectral cubes of selected regions of Titan at 250 m resolution repeated multiple times during the prime mission	Prefer mapping phase orbit within ±3 hrs from local noon

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. *Science traceability matrix: orbiter, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O3:** Characterize what chemical modification of organics occurs on the surface.	**I3:** Quantify the sources of energy for surface chemistry and identify the sites where it may have been present.	**M1:** Flux of cosmic rays.	**A1:** Use star tracker to determine flux.			
			M2: Distribution of impacts visible at the surface or buried as a result of erosional and depositional modification.	**A1:** High-resolution near-IR imaging at 2.05 ± 0.08 µm, 2.73 ± 0.08 µm, and 5.35 ± 0.45 µm.	HiRIS	Three-color maps of 80% of Titan's surface at 50 m resolution	Prefer mapping phase orbit at ±4 hrs from local noon
				A2: Single band (>20 MHz center) penetrating radar with capability of sub-surface sounding to a depth of ~5 km with ~10 m depth resolution.	TiPRA	2D and 3D maps of Titan's subsurface up to 5 km depth, with a vertical resolution of ~10 m, and a spatial resolution of ~10 km	TiPRA can take data on the nightside.
			M3: Map surface at 50 m resolution in multiple wavelengths and correlate morphology and spectral characteristics of surface features with topography.	**A1:** High-resolution near-IR imaging at 2.05 ± 0.08 µm, 2.73 ± 0.08 µm, and 5.35 ± 0.45 µm.	HiRIS	Three-color maps of 80% of Titan's surface at 50 m resolution	Prefer mapping phase orbit at ±4 hrs from local noon
			M4: Map compounds such as acetylene and polyacetylene that indicate sites of chemical energy from latitudes 85°N to 85°S with 250 m spatial resolution and long temporal coverage.	**A1:** Repeated near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 µm and 4.8–5.8 µm with spectral resolution >400 and spatial resolution = 250 m	HiRIS	Near-IR spectral cubes of selected regions of Titan at 250 m resolution repeated multiple times during the prime mission	Prefer mapping phase orbit within ±3 hrs from local noon
		I4: Quantify the amount of aerosols deposited on Titan's surface and their modification as they get buried.	**M1:** Sounding profiles of subsurface dielectric horizons with 10 m vertical resolution and extensive surface coverage. Horizontal resolution required is 5–10 km cross track, 1 km lateral (along track) with 10 m vertical precision altimetry.	**A1:** Single band (>20 MHz center) penetrating radar with capability of sub-surface sounding to a depth of ~5 km with ~10 m depth resolution.	TiPRA	2D and 3D maps of Titan's subsurface up to 5 km depth, with a vertical resolution of ~10 m, and a spatial resolution of ~10 km	TiPRA can take data on the nightside. Profiles coordinated with HiRIS data.
	O4: Characterize the complexity of species in the subsurface ocean.	**I1:** Determine whether evidence of sub-surface ocean species is present in cryovolcanic sites.	**M1:** Map compounds such as ammonia, sulfates, and more complex organics (e.g., CH_3COOH) at cryovolcanic sites with 250 m spatial resolution.	**A1:** Near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 µm and 4.8–5.8 µm with spectral resolution >400 and spatial resolution = 250 m.	HiRIS	Near-IR spectral cubes of cryovolcanic sites on Titan with 250 m spatial resolution	Prefer mapping phase orbit within ±3 hrs from local noon

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. Science traceability matrix: orbiter, cont'd.

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O5:** Characterize bulk composition, sources of nitrogen and methane, and exchange between the surface and the interior.	**I1:** Determine whether carbon dioxide is primarily internally derived or photochemically produced.	**M1:** Isotopic composition of surface carbon and oxygen species at 250 m resolution.	**A1:** Partially met with near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 μm and 4.8–5.8 μm with spectral resolution >400 and spatial resolution = 250 m.	HiRIS	Near-IR spectral cubes characterizing the surface of Titan at 250 m resolution	Prefer mapping phase orbit within ±3 hrs from local noon
			M2: Isotopic composition of atmospheric carbon and oxygen species from the surface to 1500 km.	**A1:** Mid-infrared spectra of the stratosphere with 30–1400 wave numbers (7–333 μm), spectral resolution of 0.1 to 3 wave numbers, spatial resolution of <5 mrad IFOV.	TIRS	Thermal and compositional maps and profiles of the stratosphere (50–450 km) with altitude and latitude.	Limb and nadir viewing on polar orbit, rotation in azimuth
				A2: Submillimeter sounding at 540–640 GHz with resolution 300 khz and 5% precision in retrieved abundances.	SMS	Isotopic ratios of C, H, O, N in several species	Limb viewing from polar orbit, in-track and off-track orientation
				A3: Direct sampling Mass spectrometry up to 10,000 Da with mass resolution 10,000 at 1% peak height and dynamic range of 10^8.	PMS	High and low data volume survey mode spectra: 1. Open source positive ion spectrum 2. Open source negative ion spectrum 3. Open source neutral spectrum 4. Closed source neutral spectrum 5. High mass resolution mode High Data Volume Data Rate: 48 kbits/s	Periapses varying from 700 km upward during aerosampling. Ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. *Science traceability matrix: orbiter, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O5:** Characterize bulk composition, sources of nitrogen and methane, and exchange between the surface and the interior.	**I2:** Determine whether methane is primordial or derived from carbon dioxide.	**M1:** Isotopic composition of atmospheric carbon with precision of 0.1 per mil at altitudes from 600 km upwards (particularly in well mixed region below 850 km).	**A1:** Direct sampling Mass spectrometry with sensitivity of 10 ppb at 850 km altitude. A dual inlet system with a reference gas is required for accurate isotope determination.	PMS	High and low data volume survey mode spectra: 1. Open source positive ion spectrum 2. Open source negative ion spectrum 3. Open source neutral spectrum 4. Closed source neutral spectrum 5. High mass resolution mode High Data Volume Data Rate: 48 kbits/s	Periapses varying from 700 km upward during aerosampling. Ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination.
			M2: Isotopic composition of surface carbon species at 250 m spatial resolution.	**A1:** Near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 μm and 4.8–5.8 μm with spectral resolution >400 and spatial resolution = 250 m.	HiRIS	Near-IR spectral cubes characterizing the surface of Titan at 250 m resolution	Prefer mapping phase orbit within ±3 hrs from local noon
		I3: Determine whether molecular nitrogen is derived from ammonia.	**M1:** Isotopic composition of atmospheric nitrogen from 600 km upwards to a precision of 0.1 per mil.	**A1:** Direct sampling Mass spectrometry with sensitivity of 10 ppb at 850 km altitude. A dual inlet system with a reference gas is required for accurate isotope determination.	PMS	High and low data volume survey mode spectra: 1. Open source positive ion spectrum 2. Open source negative ion spectrum 3. Open source neutral spectrum 4. Closed source neutral spectrum 5. High mass resolution mode High Data Volume Data Rate: 48 kbits/s	Periapses varying from 700 km upward during aerosampling. Ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. Science traceability matrix: orbiter, cont'd.

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O5:** Characterize bulk composition, sources of nitrogen and methane, and exchange between the surface and the interior.	**I3:** Determine whether molecular nitrogen is derived from ammonia.	**M2:** Inventory compounds such as ammonia and ammonium hydrate between +65 and -90 degrees latitude with 250 m spatial resolution.	**A1:** Near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 μm and 4.8–5.8 μm with spectral resolution >400 and spatial resolution = 250 m.	HiRIS	Near-IR spectral cubes characterizing the surface of Titan at 250 m resolution	Prefer mapping phase orbit within ±3 hrs from local noon
		I4: Determine whether pockets of partial melt are present at depth.	**M1:** Sounding profiles of subsurface dielectric horizons with 10 m vertical resolution and extensive surface coverage. Horizontal resolution required is 5–10 km cross track, 1 km lateral (along track) with 10 m vertical precision altimetry.	**A1:** Single band (>20 MHz center) penetrating radar with capability of sub-surface sounding to a depth of ~5 km with ~10 m depth resolution.	TiPRA	2D and 3D maps of Titan's subsurface up to 5 km depth, with a vertical resolution of ~10 m, and a spatial resolution of ~10 km	TiPRA can take data on the nightside. Profiles coordinated with HiRIS data.
		I5: Determine the isotopic ratios of noble gases'	**M1:** Quantify noble gas isotopic ratios (Ar, Kr, Xe)	**A1**: Direct sampling Mass spectrometry with sensitivity of 10 ppb at 850 km altitude. A dual inlet system with a reference gas is required for accurate isotope determination.	PMS	High and low data volume survey mode spectra: 1. Open source positive ion spectrum 2. Open source negative ion spectrum 3. Open source neutral spectrum 4. Closed source neutral spectrum 5. High mass resolution mode High Data Volume Data Rate: 48 kbits/s	Periapses varying from 700 km upward during aerosampling. Ram direction pointing of the instrument during aerosampling.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. *Science traceability matrix: orbiter, cont'd.*

MISSION GOALS		SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal C: What can be learned from Enceladus and from Saturn's magnetosphere about the origin and evolution of Titan?	**Saturn Magnetosphere**	**O1:** Determine how Titan's atmosphere evolves by virtue of its coupling to the Saturn magnetosphere and Titan's low gravity.	**I1:** Determine how energy is deposited in the upper atmosphere of Titan to drive the chemistry and the escape rate of major atmospheric constituents.	**M1:** 3D ion-electron plasma measurements with FOV ~2π steradians, view flow in corotation and ram directions; view upward and downward looking hemispheres (not likely to be simultaneous at all times). The 3D plasma electron measurements must cover the energy range from 1 eV to 30 keV with angular resolution ~20°x20°, energy resolution $\Delta E/E$ ~ 18% and geometric factor GF ~ 1.0e^{-3} cm^2-ster-eV/eV. Electron measurements from 0.01 eV to 40 eV will be provided by LP. The 3D plasma ion measurements must cover the energy range from 0.1 V to 30 kV, angular resolution 20°x20°, energy resolution $\Delta E/E$ ~ 18%, mass range $1 \leq M/Q \leq 10{,}000$ amu/charge, and geometric factor GF ~ 1.0e^{-3} cm^2-ster-eV/eV (ability to attenuate GF desirable for ionospheric measurements. The hot plasma and energetic particle measurements will be from 20 keV to 1 MeV for electrons and 10 MeV for ions with energy resolution $\Delta E/E$ ~30%, angular resolution ~30° and GF ~ 0.05 cm^2-ster or greater. The energetic ion measurements should have mass resolution $M/\Delta M$ ~10 or better.	**A1:** Measure ion and electron fluxes from few ev-10 MeV. Plasma instrument (E/Q <30 kV) must separate water group, methane group and ammonium group ions with TOF mass resolution $M/\Delta M$ ~10 (ST) and 60 (LEF). Energetic Particle Spectrometer (measures magnetospheric particle fluxes from 10 keV to >Mev) with $M/\Delta M$ ~ 10 as part of a combined package. The plasma instrument will need to measure the ion composition within Saturn's magnetosphere with water group ions indicating an Enceladus source and nitrogen ions and methane ions indicating a Titan source.	MAPP	• Vector magnetic field data to determine pitch angles • Flux of electrons from 0 to 1 MeV vs energy and direction • Flux of ions from 0 to 1 MeV vs energy and direction • Ion composition (protons vs O ions) • Thermal electron density and temperature vs time	Periapses from 700 km upward during aerosampling and 950 km upwards during main mission. Complete range of local times and latitudes. Downward and upward going hemispheres visible.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. *Science traceability matrix: orbiter, cont'd.*

MISSION GOALS		SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal C: What can be learned from Enceladus and from Saturn's magnetos phere about the origin and evolution of Titan?	Saturn Magnetosphere	**O1:** Determine how Titan's atmosphere evolves by virtue of its coupling to the Saturn magnetosphere and Titan's low gravity.	**I1:** Determine how energy is deposited in the upper atmosphere of Titan to drive the chemistry and the escape rate of major atmospheric constituents.	**M2:** Thermal electron density and temperature *in situ* and density profiles as a function of altitude from the ionospheric peak to the orbiter.	**A1:** Langmuir (swept voltage/current) probe as part of combined packager. (Note: to obtain implied vertical profile requires topside sounding using low frequency ionospheric sounder addition to TiPRA [similar to MARSIS])	MAPP	Thermal electron density and temperature vs time	Periapses from 700 km upward during aerosampling and 950 km upwards during main mission. Complete range of local times and latitudes.
				M3: Abundances of upper atmospheric constituents with M up to 10,000 Da; mass resolution 10,000 at 1% of peak height at altitudes from 700 km through 1000 km; sensitivity including isotopes, detectability down to 0.01 ppb.	**A1:** Direct sampling Mass spectrometry up to 10,000 Da with mass resolution 10,000 at 1% peak height and dynamic range of 10^8.	PMS	High and low data volume survey mode spectra: 1. Open source positive ion spectrum 2. Open source negative ion spectrum 3. Open source neutral spectrum 4. Closed source neutral spectrum 5. High mass resolution mode High Data Volume Data Rate: 48 kbits/s	Ram direction pointing of the instrument during flybys. Sample inlet should be located far from the main thrusters to avoid contamination.
			I2: Determine the escape rates and mechanisms of major atmospheric species on Titan.	**M1:** Vertical profiles of carbon, nitrogen and oxygen containing compounds as major and minor constituents near the exobase of Titan with accuracy better than 5%.	**A1:** Submillimeter sounding at 540–640 GHz with resolution 300 khz.	SMS	Alt/lat abundance profiles	Limb viewing from polar orbit, in-track and off-track orientation
					A2: Mid-infrared spectra of the stratosphere over the region 30–1400 wave numbers (7–333 µm), spectral resolution of 0.1 to 3 wave numbers, spatial resolution of <5 mrad IFOV.	TIRS	Thermal and compositional maps and profiles of the stratosphere (50–450 km) with altitude and latitude	Limb and nadir viewing on polar orbit, rotation in azimuth

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. *Science traceability matrix: orbiter, cont'd.*

MISSION GOALS		SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal C: What can be learned from Enceladus and Saturn's magnetosphere about the origin and evolution of Titan?	**Enceladus**	**O2:** Infer the crustal and deep internal structure of Enceladus, including the presence of gravity anomalies, and the moon's tidal history.	**I1:** Test for the presence of crustal or deeper structures associated with Enceladus' internal activity, including an interface between a solid crust and a liquid layer, as well as partial melt pockets	**M1:** Degree-two gravity coefficients (J_2, C_{22}, S_{22}). Harmonic amplitudes down to 0.1 ppm Enceladus surface gravity.	**A1:** Relative velocity between the spacecraft and ground station determined from Doppler tracking with an accuracy up to 50 µm/s with 60 s integration periods. (Ka-band link stability ~10^{-15} after all calibrations including accelerometer for non-gravitational forces).	RSA	Coefficients of spherical harmonic expansion of gravity field for further analysis and interpretation in terms of internal structure. The static degree-two gravity field will lead to constraints on the global density structure of the interior. Time variations of the degree-two field will lead to investigating the tidal response of the satellite and constraining its viscoelastic structure. Regional gravity profiles will provide constraints on the crustal structure.	Optimized gravity configuration near closest approach with minimized non-gravitational forces as well as Doppler tracking over long arcs.
				M2: Sounding profiles of subsurface dielectric horizons, in the active region, up to 50 km depth at 100 m vertical resolution and a spatial resolution better than 2 km.	**A1:** Single band (>20 MHz center) penetrating radar and altimetry with capability of sub-surface sounding to a depth of ~50 km with ~10 m depth resolution.	TiPRA	2D and 3D maps of Enceladus' subsurface to a 20 km depth on average and up to 50 km depth locally, with a vertical resolution of ~10 m, over the active region	Observations at C/A for all flybys. Use long radar echo gate in order to receive echoes from greater penetration depths. Simultaneous observation with RSA to obtain both the subsurface structure and associated gravity signature.
			I2: Test for true polar wander on Enceladus.	**M1:** Obliquity and spin of Enceladus.	**A1:** Repeated high resolution near-IR imaging at 2.05 ± 0.08 µm, 2.73 ± 0.08 µm, and 5.35 ± 0.45 µm.	HiRIS	Landmark displacement maps for Enceladus at 20 m resolution (nominal position changes as seen between different observations of same landmark)	Acquired ~600 km from Enceladus. Repeated on multiple passes.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. Science traceability matrix: orbiter, cont'd.

MISSION GOALS		SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal C: What can be learned from Enceladus and Saturn's magnetosphere about the origin and evolution of Titan?	Enceladus	**O3:** Characterize the chemistry of the Enceladus plumes.	**I1:** Determine the composition of the plume, including isotopic abundances.	**M1:** Abundances and time variability of organic and inorganic species in the plume, including heavy polymers at mass resolution 10,000 at 1% of peak height.	**A1:** Direct sampling Mass spectrometry up to 10,000 Da with mass resolution 10,000 at 1% peak height and dynamic range of 10^8.	PMS	High and low data volume survey mode spectra: 1. Open source positive ion spectrum 2. Open source negative ion spectrum 3. Open source neutral spectrum 4. Closed source neutral spectrum 5. High mass resolution mode	Ram direction pointing of the instrument during flybys. Sample inlet should be located far from the main thrusters to avoid contamination. High Data Volume Data Rate: 48 kbits/s
					A2 Submillimeter sounding at 540–640 GHz with resolution 300 khz.	SMS	Gaseous Abundances, temperatures and winds in plumes	Map plumes
		O4: Understand the formation of the active region near the south pole, and whether liquid water exists beneath the area.	**I1:** Characterize the global and regional geomorphology of Enceladus' surface.	**M1:** Map surface features at 0.5 km spatial resolution at the global scale.	**A1:** Whole-disk near-IR imaging at 2.05 ± 0.08 μm, 2.73 ± 0.08 μm, and 5.35 ± 0.45 μm.	HiRIS	Near-global near-IR three-color maps of Enceladus at 0.5 km resolution	Acquired ~15,000 km from Enceladus
				M2: Composition of surface at 1 km spatial resolution at the global scale.	**A1:** Near-IR mapping spectroscopy from 0.85–2.4 μm and 4.8–5.8 μm with spectral resolution >400.	HiRIS	Near-global near-IR spectral cubes of Enceladus at 1 km resolution	Acquired ~6,000 km from Enceladus
				M3: Map surface features at 30 m spatial resolution of candidate locations on a regional scale.	**A1:** High-resolution Near-IR imaging at 2.05 ± 0.08 μm, 2.73 ± 0.08 μm, and 5.35 ± 0.45 μm.	HiRIS	Regional three-color maps of Enceladus at 30 m resolution	Acquired ~1000 km from Enceladus
				M4: Surface topography at 10 m vertical resolution, a spatial resolution along-track up to 100 m, and cross-track up to 1 km of candidate locations on a regional scale.	**A1:** Single band (>20 MHz center) penetrating radar and altimetry with capability of sub-surface sounding to a depth of ~50 km with ~10 m depth resolution.	TiPRA	Regional topography maps of Titan's surface with a spatial resolution up to 0.1 km and a vertical resolution of ~10 m	Observations at C/A for all flybys. Simultaneous observation with RSA to obtain both the subsurface structure and associated gravity signature.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. Science traceability matrix: orbiter, cont'd.

MISSION GOALS		SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal C: What can be learned from Enceladus and Saturn's magnetosphere about the origin and evolution of Titan?	Enceladus	**O4:** Understand the formation of the active region near the south pole, and whether liquid water exists beneath the area.	**I1:** Characterize the global and regional geomorphology of Enceladus' surface	**M5:** Composition of surface geologic features at 300 m spatial resolution of candidates locations on a regional scale.	**A1:** Near-IR mapping spectroscopy from 0.85–2.4 μm and 4.8–5.8 μm with spectral resolution >400.	HiRIS	Regional near-IR spectral cubes of Enceladus at 300 m resolution	Acquired ~1,800 km from Enceladus
				M6: Sounding profiles of subsurface dielectric horizons, in the active region up to 50 km depth, at 10 m vertical resolution, a spatial resolution along-track up to 0.1 km and cross-track up to 1 km.	**A1:** Single band (>20 MHz center) penetrating radar and altimetry with capability of sub-surface sounding to a depth of ~50 km with ~10 m depth resolution.	TiPRA	2D and 3D maps of Enceladus' subsurface to a 20 km depth on average and up to 50 km depth locally, with a vertical resolution of ~10 m, over the active region	Observations at C/A for all flybys. Use long radar echo gate in order to receive echoes from greater penetration depths Simultaneous observation with RSA to obtain both the subsurface structure and associated gravity signature.
			I2: Determine whether thermal anomalies exist underneath the surface.	**M1:** Surface temperature distribution with precision 1 K; spatial resolution 100 meters.	**A1:** Mid-infrared spectra of the surface in the 30–1400 wave numbers (7–333 μm) region, spectral resolution of 3 to 15 wave numbers, spatial resolution of <5 mrad IFOV.	TIRS	Temperature maps of the surface	Nadir viewing of the surface, range less than 600 km
				M2: Sounding profiles of subsurface dielectric horizons, in the active region up to 50 km depth	**A1:** Single band (>20 MHz center) penetrating radar and altimetry with capability of sub-surface sounding to a depth of ~50 km with ~10 m depth resolution.	TiPRA	2D and 3D maps of Enceladus' subsurface to a 20 km depth on average and up to 50 km depth locally, with a vertical resolution of ~10 m, over the active region	Observations at C/A for all flybys. Use long radar echo gate in order to receive echoes from greater penetration depths Simultaneous observation with RSA to obtain both the subsurface structure and associated gravity signature.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. *Science traceability matrix: orbiter, cont'd.*

MISSION GOALS		SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
	Enceladus	**O4:** Understand the formation of the active region near the south pole, and whether liquid water exists beneath the area.	**I3:** Determine the origin of the surface organic materials and its connection with interior reservoirs.	**M1:** Gravity field amplitude down to 0.1 ppm Enceladus surface gravity.	**A1:** Relative velocity between the spacecraft and ground station determined from Doppler tracking with an accuracy up to 50 μm/s with 60 s integration periods. (Ka-band link stability ~10^{-15} after all calibrations including accelerometer for non-gravitational forces).	RSA	Regional gravity profile for further analysis and interpretation of crustal structure	Optimized gravity configuration near closest approach with minimized non-gravitational forces
				M2: Composition of surface organics at 300 m spatial resolution.	**A1:** Near-IR mapping spectroscopy from 0.85–2.4 μm and 4.8–5.8 μm with spectral resolution >400.	HiRIS	Regional near-IR spectral cubes of Enceladus at 300 m resolution	Acquired ~1,800 km from Enceladus
		O5: Identify and characterize candidate sites on Enceladus for future *in situ* exploration.	**I1:** Determine whether extrusion of water ice or liquid water has occurred recently.	**M1:** Distribution of water ice and frost at 300 m spatial resolution.	**A1:** Near-IR mapping spectroscopy from 0.85–2.4 μm and 4.8–5.8 μm with spectral resolution >400.	HiRIS	Regional near-IR spectral cubes of Enceladus at 300 m resolution	Acquired ~1,800 km from Enceladus
				M2: Sounding profiles of subsurface dielectric horizons, in the active region, up to 50 km depth at 10 m vertical resolution, a spatial resolution along-track up to 0.1 km and cross-track up to 1 km.	**A1:** Single band (>20 MHz center) penetrating radar and altimetry with capability of sub-surface sounding to a depth of ~50 km with ~10 m depth resolution.	TiPRA	2D and 3D maps of Enceladus' subsurface to a 20 km depth on average and up to 50 km depth locally, with a vertical resolution of ~10 m, over the active region	Observations at C/A for all flybys. Use long radar echo gate in order to receive echoes from greater penetration depths Simultaneous observation with RSA to obtain both the subsurface structure and associated gravity signature.
				M3: Surface temperature distribution with precision 1 K; spatial resolution 100 meters.	**A1:** Mid-infrared spectra of the stratosphere in the 30–1400 wave numbers (7–333 μm) region, spectral resolution of 3 to 15 wave numbers, spatial resolution of <5 mrad IFOV.	TIRS	Temperature maps of the surface	Nadir viewing of the surface, range less than 600 km

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

Table 2.3-1. Science traceability matrix: orbiter, cont'd.

MISSION GOALS		SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal C: What can be learned from Enceladus and Saturn's magnetosphere about the origin and evolution of Titan?	Enceladus	**O5:** Identify and characterize candidate sites on Enceladus for future *in situ* exploration.	**I2:** Determine whether areas of extremely thin crust or exposed liquid within cracks exist.	**M1:** Variations in the tiger stripe regions as a function of true anomaly at 30 m spatial resolution.	**A1:** High-resolution near-IR imaging at 2.05 ± 0.08 μm, 2.73 ± 0.08 μm, and/or 5.35 ± 0.45 μm repeated at multiple true anomalies.	HiRIS	Three-color maps of Enceladus' tiger stripe region at 30 m resolution for multiple true anomalies	Acquired ~1000 km from Enceladus. Requires multiple flybys over the south polar region.
				M2: Gravity field amplitude down to 0.1 ppm Enceladus surface gravity at candidate locations. Repeat coverage for different true anomalies.	**A1:** Relative velocity between the spacecraft and ground station determined from Doppler tracking with an accuracy up to 50 μm/s with 60 s integration periods. (Ka-band link stability ~10^{-15} after all calibrations including accelerometer for non-gravitational forces).	RSA	Coefficients of spherical harmonic expansion of gravity field for further analysis and interpretation in terms of regional crustal structure.	Optimized gravity configuration near closest approach with minimized non-gravitational forces, as well as Doppler tracking over long arcs.
				M3: Sounding profiles of subsurface dielectric horizons, in the active region, up to 50 km depth at 10 m vertical resolution, a spatial resolution along-track up to 0.1 km and cross-track up to 1 km.	**A1:** Single band (>20 MHz center) penetrating radar and altimetry with capability of sub-surface sounding to a depth of ~50 km with ~10 m depth resolution.	TiPRA	2D and 3D maps of Enceladus' subsurface to a 20 km depth on average and up to 50 km depth locally, with a vertical resolution of ~10 m, over the active region	Observations at C/A for all flybys. Use long radar echo gate in order to receive echoes from greater penetration depths Simultaneous observation with RSA to obtain both the subsurface structure and associated gravity signature.
				M4: Surface temperature distribution with precision 1 K; spatial resolution 100 meters.	**A1:** Mid-infrared spectra of the stratosphere in the 30–1400 wave numbers (7–333 μm) region, spectral resolution of 3 to 15 wave numbers, spatial resolution of <5 mrad IFOV.	TIRS	Temperature maps of the surface	Nadir viewing of the surface, range less than 600 km

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

***Table 2.3-2.** Science traceability matrix: lake lander.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O1:** Determine how energy is deposited in the upper atmosphere to drive the chemistry and the escape rate of major atmospheric constituents.	**I1:** Quantify the deposition of radiation into Titan's atmosphere.	**M4:** Vertical profile of the magnetic field magnitude and direction to quantify the magnetic shielding effect of the ionosphere and extent of the penetration of Saturn's magnetic field.	**A1:** Measure dual sensor (gradiometer) vector magnetic field along the path of the probe during the entry and descent with a good knowledge of the location of the probe to reconstruct the descent.	SPP	High time resolution (100 Hz TBC) vector, 3 axis magnetic field measurement from primary magnetic field sensor with a lower time resolution data from the secondary magnetic field sensor(s) (1 Hz TBC) to allow characterization of the contamination field coming from the probe. Max data rate 0.04 kBytes/sec.	Magnetometer on during descent, and some consideration of the magnetic cleanliness of the lander. A dual sensor magnetometer with the sensors mounted ideally on a boom or mast away from the probe body to allow characterization of the magnetic field coming from the probe to enable ground processing to remove this contaminating field and achieve a more accurate measurement of the ambient magnetic field (so-called gradiometer configuration). This could also be achieved (if a boom or mast is not feasible) by having an primary sensor at an extremity of the probe and several secondary sensors fitted along an axis of the probe to provide a gradiometer type measurement.
		I2: Quantify the escape flux of elemental hydrogen, carbon, nitrogen.	**M3:** Magnetic field of Titan during descent to correlate with orbiter data. Measure vector magnetic field perturbations of order a few nT (with a resolution of order 0.04 nT) to quantify the escape flux of elemental hydrogen, carbon and nitrogen.	**A1:** Vector magnetometry (part of a combined instrument, integrated with a low energy plasma and particles instrument, energetic particle spectrometer and Langmuir probe).	SPP	Magnetic field vector at 1 s resolution from both sensors Ion and electron thermal and supra-thermal velocity moments of density, temperature and magnetosphere-ionosphere winds.	
	O2: Characterize the relative importance of exogenic and endogenic oxygen sources.	**I2:** Quantify the flux of endogenic oxygen from the surface and interior.	**M2:** Amount of O in the lake	**A1:** GC x GC separation followed by high resolution MS and MEMS sensor analysis.	TLCA	Mass spectra as a function of GC x GC retention time over the mass range 1–500 Daltons with 10,000 mass resolution plus 1 Mb MEMS sensor image; 1% precision.	Liquid sampling from the lake.
			M3: Isotopic ratio $^{18}O/^{16}O$	**A1:** GC x GC separation followed by pyrolysis and isotopic mass spectrometry.	TLCA	Selected ion chromatograms for O isotopes; 1% precision.	Lake and atmosphere sampling
			M4: Nature and composition of O-bearing molecules	**A1:** GC x GC separation followed by high resolution MS and MEMS sensor analysis.	TLCA	Mass spectra as a function of GC x GC retention time over the mass range 1–500 Daltons with 10,000 mass resolution plus 1 Mb MEMS sensor image; 1% precision.	Lake and atmosphere sampling

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from Table 2.3-1, *Science traceability matrix: orbiter.*

Table 2.3-2. *Science traceability matrix: lake lander, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O3:** Characterize the major processes controlling the global distribution of atmospheric chemical constituents.	**I1:** Characterize the major chemical cycles.	**M1:** Methane and ethane mole fraction in the troposphere	**A4:** Direct gas inlet into MS	TLCA	Mass spectra from 1–500 Daltons with resolution >1000; precision 1%.	Atmospheric sampling during the descent.
		I2: Determine the relative importance of global transport.	**M2:** Isotopic ratios of C and N in both the liquid phase and in the aerosols that may be present in the lake	**A1:** Collect the liquid phase and the compounds in suspension and analyze with isotopic mass spectrometry. Liquid separation by GC x GC / combustion furnace / isotope ratio mass spectrometer for C and N ratios. Sol analysis by pyrolysis of filtered solids.	TLCA	Selected ion chromatograms for C and N isotopes; precision 0.1‰ for C, 0.3‰ for N.	Lake sampling with solid and liquid separation.
	O4: Characterize the atmospheric circulation and flow of energy.	**I1:** Determine the atmospheric thermal and dynamical state.	**M3:** Vertical profile of temperature, pressure (T and P accuracy to 0.1 K and 1 mP and resolution to 0.02 K and 0.1% respectively) and density in the northern hemisphere above a lake.	**A1:** Measure T by a Pt wire resistance thermometer and P by Kiel probe and capacitive gauges during the descent, monitor meteorological conditions at the surface of the lake	ASI/ MET	Vertical mass density profile and inferred pressure and temperature vertical profile during entry (upper atmosphere) and direct T and p measurements. Wind field and gusts.	ASI-ACC should be placed as close as possible to the entry module Center of Mass. ASI pressure inlet and thermometers should has access to the atmospheric unperturbed flow (outside the descent probe boundary layer) The trajectory of the probe (entry and descent module reconstructed from the engineering sensor data (e.g., IMU), the high sensitive scientific accelerometer (and/or IMU)
			M3: Vertical profile of temperature, pressure (T and P accuracy to 0.1 K and 1 mPa and resolution to 0.02 K and 0.1% respectively) and density in the northern hemisphere above a lake.	**A2:** Three-axis *in situ* accelerometer measurements during entry to a precision of 10^{-5} m/s^2 in order to reconstruct the location of the lander during its descent.	ASI/ MET	Vertical density profile and inferred pressure and temperature vertical profile starting from altitude >1600 km down to 160 km.	ASI-ACC should be placed as close as possible to the entry module Center of Mass. ASI operates before nominal interface entry altitude (1270 km).
			M4: Surface temperature of lakes to 0.1 K accuracy with a resolution of 0.02 K	**A1:** Measure the temperature at the surface of the lake with a Pt wire resistance thermometer	ASI/ MET	Temperature time series.	Continuous measurements for duration of lander lifetime.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from Table 2.3-1, *Science traceability matrix: orbiter.*

Table 2.3-2. Science traceability matrix: lake lander, cont'd.

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy.	**I2:** Determine the effect of haze and clouds.	**M3:** Extent and lateral and vertical distribution of clouds above the lakes	**A1:** Acquire image in the VIS/NIR during the probe's descent from an altitude of ~50 km	TiPI	VIS/NIR images of any clouds during the descent	The amount of light is minimal and comes from Saturn shine and diffuse scattering in Titan's atmosphere.
		I3: Determine the effects of atmospheric composition.	**M2:** Mole fraction of methane, ethane, and other compounds in the troposphere.	**A1:** Direct gas inlet into MS	TLCA	Mass spectra from 1–10,000 Daltons with resolution >1000; precision 1%	Atmospheric sampling during the descent.
		I4: Determine the effects of surface processes on meteorology.	**M3:** Temperature gradients between liquid surface and surrounding terrains with 1 K precision. Pressure and temperature at the surface of the lake	**A2:** Measure T by a Pt wire resistance thermometer and P by Kiel probe and capacitive gauges	ASI/ MET	Time series of (T, P)	Continuous measurements for duration of lander lifetime.
			M5: Nature of the molecules evaporating from the lake	**A1:** Direct gas inlet into sorption bed followed by heated injection into GC x GC MS	TLCA	Mass spectra as a function of GC x GC retention time over the mass range 1–500 Daltons with 10,000 mass resolution; precision 1%.	Collect atmospheric sample above the lake surface.
		I5: Determine the exchange of momentum, energy and matter between the surface and atmosphere and characterize the planetary boundary layer.	**M1:** Wind directions at the surface of the lake	**A1:** Measure T by a Pt wire resistance thermometer and P by Kiel probe and capacitive gauges	ASI/ MET	Direct temperature, pressure, as a function of time, inferred density	Continuous measurements for duration of lander lifetime.
			M2: Temperature of the atmosphere at the surface of the lake to 0.1 K	**A1:** T measurements with fast sampling to study the boundary layer	ASI/ MET	Direct temperature time series	Continuous measurements for duration of lander lifetime.
			M3: Wave motion on lake	**A1:** Record motion of liquid lander through accelerometers	SPP	Time series data from accelerometers	Continuous measurements for duration of lander lifetime.
			M4: Methane humidity as a function altitude and time	**A1:** Atmospheric sound speed	SPP	Sound speed data as a function of time.	Continuous measurements for duration of lander lifetime.
			M5: Distribution of condensates at the surface	**A1:** Record images of the lake just before landing	TiPI	At least three images 1024 x 1024 pixels with 60° FOV	Huygens like measurement with LEDs turned on

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from Table 2.3-1, *Science traceability matrix: orbiter.*

Table 2.3-2. Science traceability matrix: lake lander, cont'd.

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy.	**I6:** Determine the connection between weather, ionosphere and electricity.	**M1:** Electrical conductivity and permittivity of the atmosphere (positive and negative ions + electrons) to 1 km resolution in the range 10^{-14} to 10^{-6} Sm^{-1} and electrons only, with a height resolution to 100 m in the range 10^{-11} to 10^{-6} Sm^{-1}	**A1:** Relaxation probe to measure the conductivity of all charged species	ASI/ MET	Time series of voltages and conductivity (all charged species) derived from the characteristic time for charging or discharging of the probe	Measurements during descent.
				A2: Mutual impedance probe which measures the conductivity of electrons only	ASI/ MET	Amplitude and phase of electric signal	Measurements during descent
			M2: Global electric circuit and fair-weather electric field in the range from 0–10 kHz. With a height resolution of 1 km	**A1:** Measurement of electric field using dipole antennas	ASI/ MET	Time series spectra of electric field	Vertical and horizontal electric field in the frequency range from DC to VLF (~10 kHz)
			M3: Extremely low frequency-very low frequency (ELF-VLF) magnetic components from 0–10 kHz	**A1:** Measurement of magnetic field using loop antennas or search coils	ASI/ MET	Time series magnetic field spectra	Measurements during descent
			M4: Search for electric discharges	**A1:** Electric field and optical sensors	ASI/ MET	Time series electric field spectra and eventual flash detection	Coordinated with TiPI
	O5: Characterize the amount of liquid on the Titan surface today.	**I1:** Quantify the total major hydrocarbon (methane/ethane) inventory present in the lakes and seas.	**M3:** Separate ethane, ethylene acetylene, and hydrogen cyanide in the liquid mixture	**A1:** GC x GC MS	TLCA	Mass spectra as a function of GC x GC retention time over the mass range 1–100 Daltons with 10,000 mass resolution; precision 1%, sensitivity 0.1 ppb.	Lake sampling
			M4: Bulk properties such as sound speed, density, refractive index, thermal conductivity, permittivity	**A1:** Acoustic force transducers (1–10 MHz), archimedes float, refractometer, line heat source, capacitor stack	SPP	Time series 5 x 16 bit signals vs. mission time at 1 Hz, in addition one full acoustic sample ~80 kB) every 10 s to 20 s desirable.	Sensors need to be exposed to liquid after landing. Acoustic sensors need to be facing each other with clear path between them.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from Table 2.3-1, *Science traceability matrix: orbiter.*

Table 2.3-2. Science traceability matrix: lake lander, cont'd.

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O5:** Characterize the amount of liquid on the Titan surface today.	**I1:** Quantify the total major hydrocarbon (methane/ethane) inventory present in the lakes and seas.	**M5:** Permittivity and electric conductivity) in the range 10^{-14} to 10^{-6} Sm^{-1} of the surface (liquid or solid substrate	**A1:** Mutual impedance probe which measures permittivity and the conductivity of electrons and relaxation probe which measures the conductivity of all charged species	ASI/ MET	Amplitude and phase of electric signal and time series of voltages and conductivity derived from the characteristic time for charging/discharging of the probe	Lake sampling
		I2: Determine the depth of the lake at the landing site.	**M1:** Acoustic sounding	**A1:** SONAR: 10–20 khz acoustic pulse every 1 to 10 s.	SPP	Time series: signal propagation time vs. mission time @ 1 Hz	Sonar needs to be immersed into lake, facing vertically downward.
			M2: Monitor probe motion at and after splashdown	**A1:** Accelerometers	SPP	Time series: 3 x 16 bit @ 1 to 100 Hz	Location at center of mass of probe
	O6: Characterize the major processes transforming the surface throughout time.	**I2:** Characterize the origin of major surface features, including the effects of liquid flow, tectonic, volcanic, and impact events.	**M3:** Map the distribution of different surface features around the landing site	**A1:** Record images before and after landing	TiPI	At least 2 images before landing covering 60° with 1024x1024; 3 LED wavelength BGR/NIR 20 time delayed additional images; just the difference to the last initial image will be transmitted	Use Saturn shine to map Titan's surface.
	O7: Determine the existence of a subsurface liquid water ocean.	**I3:** Determine the induced magnetic field signatures in order to confirm subsurface liquid and place constraints on the conductivity and depth of the liquid	**M3:** Vector magnetic field measurements on the Titan surface to quantify the induced magnetic field and hence constrain the presence of a sub-surface conducting layer (possibly liquid water ocean)	**A1:** Measure dual sensor (gradiometer) vector magnetic field on Titan's surface	SPP	Dual sensor three-axis magnetic field data at 1 Hz (14 bit/axis)	Knowledge of probe attitude and location. Continuous magnetic field data (desirable, to combine data with magnetic field measurements from the montgolfière and orbiter). Also desirable (not required) to have some measurements with the lake lander, montgolfière, and orbiter in a line radiating from Saturn. Consideration of magnetic cleanliness requirement, and use of gradiometer configuration.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from Table 2.3-1, *Science traceability matrix: orbiter.*

***Table 2.3-2.** Science traceability matrix: lake lander, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O8:** Determine the state of internal differentiation, whether Titan has a metal core and an intrinsic magnetic field, and constrain the crustal expression of thermal evolution of Titan's interior.	**I3:** Quantify exchange between interior and atmosphere.	**M1:** D/H in methane and ethane to 0.1 per mil in the atmosphere and the lake	**A1:** Isotope ratio mass spectrometry with GC separation of Hydrogen in atmosphere and pyrolytic reduction to measure D/H in methane and ethane.	TLCA	Selected ion chromatograms for D/H isotopes; precision 5‰	Lake sampling
			M2: Measure noble gases	**A1:** Direct inlet into noble gas concentrator / getter and then into an MS	TLCA	Mass spectra from 1 to 150 Daltons with mass resolution of 200 and sensitivities exceeding 1 ppb; precision 1%	*In situ* analysis of noble gases during the descent and at the surface of the lake
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O1:** Determine the chemical pathways leading to formation of complex organics at all altitudes in the Titan atmosphere and their deposition on the surface.	**I1:** Assay the speciation and abundance of atmospheric trace molecular constituents.	**M3:** Detailed molecular analysis of the lake and atmosphere above the lake	**A1:** GC x GC separation followed by high resolution MS.	TLCA	Mass spectra as a function of GC x GC retention time over the mass range 1–500 Daltons with 10,000 mass resolution; sensitivity 1 ppb, precision 1%	Liquid and atmosphere sampling
		I3: Quantify the sources of chemical energy for atmospheric chemistry.	**M4:** Search for electric discharges during descent	**A1:** Electric field	ASI/ MET	Time series spectra	Altitude and attitude measured during the descent by accelerometers and gyros.
				A2: Acquire image in the VIS/NIR during the probe's descent	TiPI	VIS/NIR image of any clouds during the descent	Knowledge of position during descent.
		14: Determine surface composition.	**M2:** Map the distribution of different surface features	**A1:** Record images just after landing	TiPI	At least three images covering 60° with 1024 x 1024 pixels if the landing site; three LED wavelength BGR/NIR	LEDs turned on
		I5: Determine the composition of organics in the lake and the isotopic ratios of major elements.	**M1:** Isotopic ratio of C, N, and O in the organic molecules to 0.1 per mil	**A1:** GC x GC separation followed by conversion and isotopic mass spectrometry. Combustion for C and N analysis and pyrolysis for O analysis.	TLCA	Selected ion chromatograms for C, N, and O isotopes; precision 0.1‰ for C, 0.3‰ for N, 1% for O	Lake sampling

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from Table 2.3-1, *Science traceability matrix: orbiter.*

Table 2.3-2. *Science traceability matrix: lake lander, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O2:** Characterize the degree to which the Titan organic inventory is different from known abiotic material in meteorites.	**I1:** Assay the composition of organic deposits exposed at the surface, including dunes, lakes, and seas.	**M2:** Inventory organic content of the lakes, including potential solid species in suspension	**A1:** GC x GC-MS for liquids. Pyrolysis GC x GC – MS for solids	TLCA	Mass spectra as a function of GC x GC retention time over the mass range 1–500 Daltons with 10,000 mass resolution; sensitivity 1 ppb, precision 1%	Lake sampling with solid and liquid separation before analysis
			M3: Determine otical and electrical properties of the liquid (transparency, refraction)	**A1:** Measure refractive index, permittivity, and conductivity	SPP	Time series of readout of CCD array	2 kB @ 1 Hz
			M4: Determine optical properties of the lake materials to identify time dependent variations	**A1:** Measure surface albedo variations just before and after landing	TiPI	At least three images before and after landing covering 60° with 1024 x1024 pixels if the landing site; three LED wavelength BGR/NIR. 20 time delayed additional images; just the difference to the last initial image will be transmitted	LEDs turned on
		I2: Determine the chirality of organic molecules.	**M1:** Chirality of complex organics	**A1:** GC x GC-MS with derivatization and chiral columns.	TLCA	Mass spectra as a function of GC x GC retention time over the mass range 1–500 Daltons with 10,000 mass resolution plus 1Mb MEMS sensor image; sensitivity 0.1 ppm, precision 1%, 5% with MEMS.	Lake sampling
	O3: Characterize what chemical modification of organics occurs at the surface.	**I1:** Determine the roles of cratering and cryovolcanism in modification and hydrolysis of organics.	**M3:** Search for complex oxygenated organics dissolved or in suspension	**A1:** GC x GC-MS for liquids. Pyrolysis GC x GC – MS for solids	TLCA	Mass spectra as a function of GC x GC retention time over the mass range 1–500 Daltons with 10,000 mass resolution; sensitivity 1 ppb	Lake sampling with solid and liquid separation before analysis

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from Table 2.3-1, *Science traceability matrix: orbiter.*

Table 2.3-2. *Science traceability matrix: lake lander, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATIONS	PLANNING MEASUREMENT APPROACH	PLAN INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O5:** Characterize bulk composition, sources of nitrogen and methane, and exchange between the surface and the interior.	**I1:** Determine whether carbon dioxide is primarily internally derived or photochemically produced.	**M2:** Isotopic composition of atmospheric carbon and oxygen species from the surface to 1500 km.	**A2:** GC x GC separation of lake samples followed by conversion and isotopic mass spectrometry. Combustion for C analysis and pyrolysis for O analysis.	TLCA	Selected ion chromatograms for C, N, and O isotopes; precision 0.1‰ for C, 1% for O	Lake sampling
		I2: Determine whether methane is primordial or derived from carbon dioxide.	**M3:** Isotopic composition in lake of carbon in methane to 0.1 per mil and compare with isotopic composition in the atmosphere	**A1:** Isotope ratio mass spectrometry with GC separation of methane in atmosphere or lake liquid and combustion to measure C isotopes	TLCA	Selected ion chromatograms for C,N, and O isotopes; precision 0.1‰ for C	Lake and atmosphere sampling
			M4: Isotopic ratio of C in other lake organics	**A1:** GC x GC separation followed by combustion and isotopic mass spectrometry.	TLCA	Selected ion chromatograms for C, N, and O isotopes; precision 0.1‰ for C	Lake sampling
		I3: Determine whether molecular nitrogen is derived from ammonia.	**M3:** Isotopic composition of atmospheric nitrogen and noble gas isotopic ratios (Ar, Kr, Xe) to a precision of 0.1 per mil	**A1:** Direct inlet into noble gas concentrator / getter and then into a MS	TLCA	Direct inlet into noble gas concentrator / getter and then into an MS	Measurement made during descent and on the surface.
			M4: Analyze dissolved N_2 and ammonia in the lakes and determine their isotopic composition	**A1:** Membrane inlet with cold trapping of ammonia followed by pyrolysis and isotopic mass spectrometry.	TLCA	Selected ion chromatograms for C, N, and O isotopes; precision 0.3‰ for N, 5‰ for H	Lake sampling
		I5: Determine the isotopic ratios of noble gases	**M1:** Quantify noble gas isotopic ratios (Ar, Kr Xe)	**A2:** Direct inlet into noble gas concentrator / getter and then into a MS	TLCA	Direct inlet into noble gas concentrator / getter and then into an MS	Measurement made during descent and on the surface.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from Table 2.3-1, *Science traceability matrix: orbiter.*

***Table 2.3-3.** Science traceability matrix: montgolfière.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATION	PLANNING MEASUREMENT APPROACH	PLAN. INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O2:** Characterize the relative importance of exogenic and endogenic oxygen sources.	**I1:** Quantify the flux of exospheric oxygen into the atmosphere.	**M3:** O content of the aerosols	**A1:** *In situ* analysis of the aerosols collected at the level of the montgolfière	TMCA	Mass spectra over the mass range 10–600 Daltons	Collect aerosols that are falling from higher altitudes; 1 km and 5° attitude knowledge of montgolfière.
			M4: Amount of O bearing molecules in the troposphere	**A1:** Infrared spectra of the atmosphere, including CO and CO_2	BIS	Near-IR atmosphere vertical profiles between 1 and 5.6 µm with a spectral sampling of 10.5 nm	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
		I2: Quantify the flux of endogenic oxygen from the surface and interior.	**M1:** Inventory of surface constituents containing oxygen, including major isotopologues at 250 m or better resolution	**A2:** Infrared spectral maps of the surface at wavelengths absorbed by the O bearing molecules (4.92 µm for CO_2) at 10% level within a pixel	BIS	Near-IR atmosphere vertical profiles between 1 and 5.6 µm with a spectral sampling of 10.5 nm	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
	O3: Characterize the major processes controlling the global distribution of atmospheric chemical constituents.	**I1:** Characterize the major chemical cycles.	**M1:** Vertical, latitudinal, and temporal dependence of condensed and gaseous species in the atmosphere from 0 to 1500 km with precision better than 10%	**A5:** Pump the atmosphere into the chemical analyzer to analyze ethane mole fraction and other volatile species in troposphere (gas and condensed phase), with a precision of 5%	TMCA	Mass spectra over the mass range 10–600 Daltons.	Tracking of the montgolfière (lat, long, alt); 1 km and 5°attitude knowledge required.
		I2: Determine the relative importance of global transport.	**M3:** Ethane mole fraction in the troposphere (gas and condensed phases) at different longitudes (day/night variations); ethane/methane	**A1:** Pump the atmosphere into the chemical analyzer to analyze ethane mole fraction in troposphere (gas and condensed phase), with a precision of 5%	TMCA	Mass spectra over the mass range 10–100 Daltons.	Tracking of the montgolfière (lat, long, alt); 1 km and 5° attitude knowledge of montgolfière
	O4: Characterize the atmospheric circulation and flow of energy.	**I1:** Determine the atmospheric thermal and dynamical state.	**M5:** Track the drift of the montgolfière to infer strength and directions of winds.	**A1**: The location of the montgolfière relative to Titan by tri-axial accelerometers and gyroscopes (inertial platform) to infer wind field and gusts.	ASI/ MET	Trajectory and attitude reconstruction, wind field and gusts	ASI should be placed as close as possible to the center of gravity of the gondola. 1 km and 5° attitude knowledge of montgolfière.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from **Table 2.3-1**, *Science traceability matrix: orbiter, and* **Table 2.3-2**, *Science traceability matrix: lake lander.*

Table 2.3-3. *Science traceability matrix: montgolfière, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATION	PLANNING MEASUREMENT APPROACH	PLAN. INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy.	**I1:** Determine the atmospheric thermal and dynamical state.	**M6:** Measure deposition of sunlight as a function of altitude to infer the radiation balance in the troposphere.	**A1:** Solar light arriving at the altitude of the montgolfière during its journey in the tropical regions	BIS	Near-IR atmosphere vertical profiles between 1 and 5.6 µm with a spectral sampling of 10.5 nm	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required. 1 km and 5° attitude knowledge of montgolfière.
			M7: Vertical profile of temperature, pressure, and density (T and P accuracy to 0.1 K and 1 mPa and resolution to 0.02 K and 0.1% respectively). Determine the trajectory of the montgolfière during entry and descent and floating phase	**A1:** Measure T by a Pt wire resistance thermometer and P by Kiel probe and capacitive gauges. Pressure and temperature measurements during the descent. Monitor meteorological conditions during the montgolfière journey	ASI/ MET	Direct T and P measurements as a function of time and inferred wind field along the probe track	ASI pressure inlet and thermometers should have access to the atmospheric unperturbed flow (outside the descent probe boundary layer). The trajectory of the probe (entry and descent module reconstructed from the engineering sensor data (e.g., IMU), the high sensitive scientific accelerometer (and/or IMU). Coordination with orbiter RSA data.
				A2: Three-axis *in situ* accelerometer measurements to a precision of 10^{-5} m/s^2 during entry and during the montgolfière journey	ASI/ MET	Vertical mass density profile and inferred pressure and Temperature vertical profile starting from altitude >1600 km down to 160 km Plots of the trajectory and attitude of the probe during entry, descent and floating phase	ASI-ACC should be placed as close as possible to the entry module CoG. ASI operating before nominal interface entry altitude (1270 km). Coordination with orbiter RSA data.
			M8: Pressure, temperature variations in space and time (T and P accuracy to 0.1 K and 1 mPa and resolution to 0.02 K and 0.1% respectively)	**A1:** Pressure, temperature, and accelerometry during the journey of the montgolfière	ASI/ MET	Direct T and P measurements as a function of time and inferred wind field along the probe track	1 km and 5° attitude knowledge of montgolfière.
			M9: Determine large surface temperature	**A1:** Infrared spectra of the surface between 5 and 5.6 µm will enable us to see T variations larger than 50 K.	BIS	Infrared maps of the surface between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from Table 2.3-1, *Science traceability matrix: orbiter, and* Table 2.3-2, *Science traceability matrix: lake lander.*

Table 2.3-3. Science traceability matrix: montgolfière, cont'd.

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATION	PLANNING MEASUREMENT APPROACH	PLAN. INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy.	**I1:** Determine the atmospheric thermal and dynamical state.	**M10:** Timing (local time, orbital phase) of cloud occurrence, evolution, cloud base/top and appearance	**A1:** Continuous monitoring of cloud formation	VISTA-B	1360 x 1024 multi-spectral images 48°FOV	1 km and 5° attitude knowledge of montgolfière required.
				A2: Continuous monitoring of meteorological conditions	ASI/ MET	Direct T and P measurements and inferred wind field along the probe track	1 km and 5° attitude knowledge of montgolfière
		I2: Determine the impact of haze and clouds.	**M4:** Track the motion of clouds (and cryovolcanic vents, if any). Search for orographic clouds.	**A1:** Imaging from the gondola at 10 m resolution	VISTA-B	1360 x 1024 multi-spectral images 48°FOV	1 km and 5° attitude knowledge of montgolfière
				A2: Infrared spectral maps of the clouds and terrain	BIS	Infrared maps of the surface between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
			M5: Particle size distribution and optical properties of clouds and haze	**A1:** Infrared measurements of reflective light	BIS	Infrared maps between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
			M6: Profile of methane mole fraction and its variations in the equatorial regions; fraction of methane in the condensed phase compared to the total atmospheric methane abundance	**A1:** Infrared spectral maps to measure the width of the methane absorption bands to determine the amount of methane	BIS	Infrared spectra between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
				A2: Pump the atmosphere into the chemical analyzer to analyze methane mole fraction in troposphere (gas and condensed phase), with a precision of 1%	TMCA	Mass spectra over the mass range 12–20 Daltons	Tracking of the montgolfière (lat, long, alt); 1 km and 5° attitude knowledge required.
				A3: *In situ* monitoring of T and P conditions. Simultaneous measurements of pressure and T are necessary to assess the phase of the species (e.g., conden-sation) and to associate a certain pressure level in the atmosphere (or equivalent altitude level) to the mole fractions determined by TMCA.	ASI/ MET	T and P time series	1 km and 5° attitude knowledge of montgolfière

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from Table 2.3-1, *Science traceability matrix: orbiter, and* Table 2.3-2, *Science traceability matrix: lake lander.*

Table 2.3-3. Science traceability matrix: montgolfière, cont'd.

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATION	PLANNING MEASUREMENT APPROACH	PLAN. INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy.	**I3:** Determine the effects of atmospheric composition.	**M3:** Profile of ethane mole fraction and its variations in the equatorial regions; fraction of ethane in the condensed phase compared to the total atmospheric ethane abundance	**A1:** Infrared spectral maps to measure the width of the ethane absorption bands to determine the amount of ethane	BIS	Near-IR image spectra between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
				A2: Pump the atmosphere into the chemical analyzer to analyze ethane mole fraction in troposphere (gas and condensed phase), with a precision of 1%	TMCA	Mass spectra over the mass range 20–30 Daltons	Tracking of the montgolfière (lat, long, alt); 1 km and 5° attitude knowledge required.
				A3: *In situ* monitoring of T and P conditions Simultaneous measurements of pressure and T are necessary to assess the phase of the species (e.g., condensation) and to associate a certain pressure level in the atmosphere (or equivalent altitude level) to the mole fractions determined by TMCA.	ASI/ MET	T and P time series	1 km and 5° attitude knowledge of montgolfière.
			M4: Determine the topography and find correlation with clouds and turbulences.	**A1:** Topography and clouds are determined by the stereo imaging	VISTA-B	1360 x 1024 stereo images 48°FOV; 3D digital terrain and cloud models; cloud albedo time series	1 km and 5° attitude knowledge of montgolfière
				A2: Topography is determined by first echo of the radar sounder	TRS	Time series of the first return radar echoes	Precise identification of the trajectory of the montgolfière increases the quality of the measurements; 1 km and 5° attitude knowledge required.
				A3: Infrared spectrometry to monitor the clouds	BIS	Infrared spectra between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from Table 2.3-1, *Science traceability matrix: orbiter, and* Table 2.3-2, *Science traceability matrix: lake lander.*

Table 2.3-3. *Science traceability matrix: montgolfière, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATION	PLANNING MEASUREMENT APPROACH	PLAN. INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy.	**I3:** Determine the effects of atmospheric composition.	**M4:** Determine the topography and find correlation with clouds and turbulences.	**A4:** *In situ* monitoring of meteorological conditions (T, P, and wind) to investigate thermal variations, turbulence and dynamics (e.g., gravity waves and tides)	ASI/ MET	T and P plots as a function of time	1 km and 5° attitude knowledge of montgolfière.
		I4: Determine the effects of surface processes on meteorology.	**M4:** Identify active volcanism in the equatorial region with 50 m resolution from orbit and .2.5 m resolution from 10km altitude	**A1:** Infrared spectral maps	BIS	Infrared maps of the surface between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context
				A2: Stereo and high-res imaging from the Gondola	VISTA-B	Digital images and surface albedo time series	1 km and 5° attitude knowledge requirement of montgolfière
			M6: Search for possible surface methane sources (vents, etc.) in the equatorial regions.	**A1:** Stereo and high-res imaging from the Gondola	VISTA-B	Digital images and surface albedo time series	1 km and 5° attitude knowledge of montgolfière
				A2: Monitor atmospheric methane concentration.	TMCA	Mass spectra Mass spectra over the mass range 12–20 Daltons, with a precision of 1%	Precise location of montgolfière to 1 km and 5° attitude knowledge.
				A3: *In situ* monitoring of meteorological conditions by direct T and P measurements (T and P accuracy to 0.1 K and 1 mPa and resolution to 0.02 K and 0.1% respectively) and gondola attitude	ASI/ MET	T and P time series plots and inferred wind field along montgolfière track	Precise location of montgolfière to 1 km and 5° attitude knowledge.
				A4: Infrared spectral maps to measure the width of the methane absorption bands to determine the amount of methane	BIS	Infrared maps of the surface between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context
			M7: Global distribution of surface wind directions	**A1:** Direction of dunes/cloud movement	VISTA-B	1360 x 1024 stereo images 48°FOV; high resl'n 1 x 1024 line scans 7° FOV	Precise location of montgolfière to 1 km and 5° attitude knowledge .

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from **Table 2.3-1**, *Science traceability matrix: orbiter, and* **Table 2.3-2**, *Science traceability matrix: lake lander.*

Table 2.3-3. Science traceability matrix: montgolfière, cont'd.

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATION	PLANNING MEASUREMENT APPROACH	PLAN. INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy.	**I5:** Determine the exchange of momentum, energy and matter between the surface and atmosphere and characterize the planetary boundary layer.	**M7:** Global distribution of surface wind directions	**A2:** Wind field inferred from T and P measurements (T and P accuracy to 0.1 K and 1 mPa and resolution to 0.02 K and 0.1% respectively) and monitoring the gondola attitude	AS/ MET	Wind field along the montgolfière track and eventual wind gusts	Wind field inferred from T and P measurements and monitoring the gondola attitude; 1 km and 5° attitude knowledge requirement of montgolfière
			M6: Global distribution of surface roughness and topography	**A1:** Radar measurements	TRS	Time series of the amplitude of return radar echoes.	Precise location of montgolfière—1 km and 5° attitude knowledge required.
				A2: Stereo imaging (10 m/pix)	VISTA-B	1360 x 1024 stereo images 48°FOV; high res 1 x 1024 line scans; 3D dune structure	Precise location of montgolfière—1 km and 5° attitude knowledge required.
				A3: Measure the shadows of reliefs within the infrared maps	BIS	Infrared maps of the surface between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
			M7: Diurnal temperature variations and time-series meteorology	**A1:** Measure the temperature by a Pt wire resistance thermometer with $\Delta T = 0.1$ K	ASI/ MET	T and P plots as a function of time	Same as ASI/MET above
			M8: Distribution of condensates at the surface	**A1:** Infrared identification of condensate species	BIS	Infrared maps of the surface between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
				A2: High spatial resolution color images of the surface at equatorial latitudes; ground truth for orbiter measurement	VISTA-B	1360 x 1024 multispectral images 48°FOV Color images and albedo time series	Precise location of montgolfière to 1 km and 5° attitude knowledge of montgolfière
			M9: Abundance of water ice at the surface	**A1:** Infrared mapping through the methane windows and compare windows where ice absorbs (e.g., 1.6 and 2.0 µm) and where it does not (1.05 µm).	BIS	Infrared maps of the surface between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from Table 2.3-1, *Science traceability matrix: orbiter, and* Table 2.3-2, *Science traceability matrix: lake lander.*

Table 2.3-3. Science traceability matrix: montgolfière, cont'd.

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATION	PLANNING MEASUREMENT APPROACH	PLAN. INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy.	**I6:** Determine the connection between weather, ionosphere, and electricity.	**M2:** Global electric circuit and fair-weather electric field in the range from 0–10 kHz. With a height resolution of 1 km	**A1:** Measurement of electric field using dipole antennas; vertical and horizontal electric field in the frequency range from DC to VLF (~10 kHz)	TEEP-B	Time series spectra of electric field	1 km and 5° attitude knowledge of montgolfière
			M3: Extra low and low frequency (ELF-VLF) magnetic components of the atmospheric electricity from 0–10 kHz	**A1:** Measurement of magnetic field using loop antenna; vertical and horizontal electric field in the frequency range from DC to VLF (~10 kHz nas or search coils)	TEEP-B	Time series magnetic field spectra	1 km and 5° attitude knowledge of montgolfière
			M4: Search for electric discharges.	**A1:** Long exposure nighttime imaging	VISTA-B	1360 x 1024 images 48°FOV Flash saturated images	Precise location of montgolfière from Inertial Navigation System (INS); 1 km requirement
				A2: Electric field and optical sensors	TEEP-B	Time series electric field spectra	Coordinated with VISTA-B
			M5: Electrical conductivity and permittivity of the atmosphere (positive and negative ions + electrons) to 1 km resolution in the range 10^{-14} to 10^{-6} Sm^{-1} and electrons only, with a height resolution to 100 m in the range 10^{-11} to 10^{-6} Sm^{-1}	**A1:** Relaxation probe to measure the conductivity of all charged species	TEEP-B	Time series of conductivity (all charged species)	Time series of conductivity (all charged species)
				A2: Mutual impedance probe which measures the conductivity of electronics only	TEEP-B	Amplitude and phase of electric signal	Amplitude and phase of electric signal
	O5: Characterize the amount of liquid on the Titan surface today.	**I3:** Determine surface composition that might reveal the presence of liquids.	**M1:** Optical maps in the methane windows at 2.5 m resolution	**A1:** Use the infrared images at different incidence angles to determine the nature of the surface (liquid or solid)	BIS	Infrared maps of the surface between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
			M2: Precipitation rate, solid or liquid nature of precipitation	**A1:** *In situ* monitoring of T and P conditions with reference to the altitude level	ASI/ MET	T and P time series	1 km and 5° attitude knowledge of montgolfière
				A3: *In situ* observations at all wavelengths.	VISTA-B	1360 x1024 multispectral images 48°FOV	Precise location of montgolfière to 1 km and 5° attitude knowledge of montgolfière

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from Table 2.3-1, *Science traceability matrix: orbiter, and* Table 2.3-2, *Science traceability matrix: lake lander.*

***Table 2.3-3.** Science traceability matrix: montgolfière, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATION	PLANNING MEASUREMENT APPROACH	PLAN. INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O5:** Characterize the amount of liquid on the Titan surface today.	**I4:** Determine the nature of precipitation responsible for the formation of valley networks in the tropical regions.	**M1:** Lateral variations of surface compounds in the valley networks at 5 m resolution	**A1:** Map lateral variations of surface composition in the river networks and at their mouth	BIS	Infrared maps of the surface between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
				A3: High spatial resolution color images of the surface at equatorial latitudes; ground truth for orbiter measurement	VISTA-B	1360 x 1024 multispectral images 48°FOV; Color images and albedo time series	Precise location of montgolfière to 1 km and 5° attitude knowledge.
	O6: Characterize the major processes transforming the surface throughout time.	**I1:** Determine the origin of major crustal features; correlate regional elevation changes with geomorph-ology and compositional variations.	**M5:** Measure regional topography	**A1:** Stereo images of the surface	VISTA-B	1360 x 1024 stereo images 48°FOV; 3D digital terrain model	Precise location of montgolfière to 1 km and 5° attitude knowledge. .
				A2: Reflection of radar signal	TRS	Time series of the first return radar echoes	Precise identification of the trajectory of the montgolfière increases the quality of the measurements
		I2: Characterize the origin of major surface features, including the effects of liquid flow, tectonic, volcanic, and impact events.	**M4:** Geological maps at 2.5 m resolution	**A1:** Infrared mapping through the methane windows	BIS	Infrared maps of the surface between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
		I3: Determine the internal magnetic signal.	**M1:** Magnetic map, taken from a constant altitude	**A1:** Dual sensor magnetometer fixed to boom on gondola	MAG	Normal mode 16 Hz data from primary sensor and 1 Hz data from secondary sensor, with burst mode of 128 Hz data from primary sensor triggered by command or autonomously. Normal mode 900 bits per second (bps), burst mode 6500 bps.	Precise location of montgolfière to 1 km and 5° attitude knowledge 1 km continuous magnetic field data, as much coverage of the surface as possible. Consideration of magnetic cleanliness requirements vs. boom length. Complementarities with orbiter measurements during Titan flybys.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from Table 2.3-1, *Science traceability matrix: orbiter, and* Table 2.3-2, *Science traceability matrix: lake lander.*

Table 2.3-3. *Science traceability matrix: montgolfière, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATION	PLANNING MEASUREMENT APPROACH	PLAN. INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O6:** Characterize the major processes transforming the surface throughout time.	**I4:** Detect and measure the depth of shallow subsurface reservoirs of liquid (hydrocarbons).	**M2:** Subsurface sounding at frequency between 150 and 200 MHz in order to detect liquid reservoirs less than 1 km deep.	**A1:** High resolution subsurface profiles over few hundred meters (500 m) spot size and vertical resolution <6 m	TRS	Time series of radar profiles representing the sub-surface interfaces	Precise location of the montgolfière makes it possible an integrated multiscale analysis of the TRS profiles with the radar measurements acquired by the sounder on the orbiter. Precise location of montgolfière to 1 km and 5° attitude knowledge.
		I5: Determine the subsurface structures and constrain the stratigraphic history of dunes.	**M1:** Subsurface sounding along the montgolfière journey at a frequency between 150 and 200 MHz (vertical resolution of less than 10 meters and spatial resolution less than 200 meters)	**A1:** Radar sounding	TRS	Time series of radar profiles representing the sub-surface stratification	Comparison between optical remote sensing images and radar profiles. Precise location of the montgolfière makes it possible an integrated multiscale analysis of the TRS profiles with the radar measurements acquired by the sounder on the orbiter. Precise location of montgolfière to 1 km and 5° attitude knowledge.
	O7: Determine the existence of a subsurface liquid water ocean.	**I2:** Determine if the crust is decoupled from the interior and the thickness and rigidity of the icy crust.	**M1:** Map of geological structures at different true anomalies	**A1:** High-resolution mapping of surface features with their precise location	VISTA-B	Geological image maps	Precise location of montgolfière to 1 km and 5° attitude knowledge.
		I3: Determine the induced magnetic field signatures in order to confirm subsurface liquid and place constraints on the conductivity and depth of the liquid	**M3:** *In situ* vector magnetic field measurements	**A1:** Dual sensor magnetometer fixed to boom on gondola	MAG	Normal mode 16 Hz data from primary sensor and 1 Hz data from secondary sensor, with burst mode of 128 Hz data from primary sensor triggered by command or autonomously. Normal mode 900 bits per second (bps), burst mode 6500 bps.	Precise location of montgolfière to 1 km and 5° attitude knowledge. Continuous magnetic field data combined with magnetic field measurements from the orbiter and lander. Nightside data at 0600 Saturn Local Time highly desirable. Desirable (not required) to have some measurements with the lander, montgolfière, and orbiter in a line radiating from Saturn.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from Table 2.3-1, *Science traceability matrix: orbiter, and* Table 2.3-2, *Science traceability matrix: lake lander.*

Table 2.3-3. Science traceability matrix: montgolfière, cont'd.

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATION	PLANNING MEASUREMENT APPROACH	PLAN. INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O8:** Determine the state of internal differentiation, whether Titan has a metal core and an intrinsic magnetic field, and constrain the crustal expression of thermal evolution of Titan's interior.	**I2:** Determine whether Titan has a dynamo.	**M2:** *In situ* vector magnetic field measurements	**A1:** Dual sensor magnetometer fixed to boom on gondola	MAG	Normal mode 16 Hz data from primary sensor and 1 Hz data from secondary sensor, with burst mode of 128 Hz data from primary sensor triggered by command or autonomously. Normal mode 900 bits per second (bps), burst mode 6500 bps.	Precise location of montgolfière to 1 km and 5° attitude knowledge. Continuous magnetic field data combined with magnetic field measurements from the orbiter and lander. Nightside data at 0600 Saturn Local Time highly desirable. Desirable (not required) to have some measurements with the lander, montgolfière, and orbiter in a line radiating from Saturn.
		I3: Quantify exchange between interior and atmosphere.	**M3:** Measure noble gases and isotopes (esp., Ar, Kr, Xe) to ppb levels in gas phase and aerosols	**A1:** *In situ* measurement of aerosols and atmospheric gas phase, with a precision of 1%	TMCA	Mass spectra over the mass range 10–150 Daltons	Good location to 1 km and 5° attitude knowledge of montgolfière
			M4: Subsurface layering	**A1:** High resolution subsurface profiles over few hundred meters (500 m) spot size and vertical resolution <6 m	TRS	Time series of radar profiles representing the sub-surface stratification	Precise location of the montgolfière to integrate multiscale analysis of the TRS profiles with the radar measurements acquired by the sounder on the orbiter; 1 km and 5° attitude knowledge of montgolfière
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O1:** Determine the chemical pathways leading to formation of complex organics at all altitudes in the Titan atmosphere and their deposition on the surface.	**I1:** Assay the speciation and abundance of atmospheric trace molecular constituents.	**M4:** Concentration of molecular constituents in the troposphere with S/N ratio >100	**A1:** IR reflectance spectra with long integration times to enable spectral summing over homogeneous regions.	BIS	Infrared spectra between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
			M5: Latitudinal and vertical distribution of minor species and its temporal variation	**A1:** *In situ* analysis of minor species	TMCA	0–600 Da Mass spectra	Same location of the montgolfière at different times; analysis of only low molecular mass species
			M6: Day-night variation of minor species to infer information about condensation	**A1:** *In situ* analysis of minor species gas and condensed phase	TMCA	Mass spectra	Same location of the montgolfière during at least one full Titan day

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from Table 2.3-1, *Science traceability matrix: orbiter, and* Table 2.3-2, *Science traceability matrix: lake lander.*

***Table 2.3-3.** Science traceability matrix: montgolfière, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATION	PLANNING MEASUREMENT APPROACH	PLAN. INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O1:** Determine the chemical pathways leading to formation of complex organics at all altitudes in the Titan atmosphere and their deposition on the surface.	**I1:** Assay the speciation and abundance of atmospheric trace molecular constituents.	**M7:** Monitor T and P conditions to help determine species abundances and condensation.	**A1:** *In situ* measurements of T and P with reference to the altitude level. Simultaneous measurements of P and T are necessary to assess the phase of the species (e.g., condensation) and to associate a certain pressure level in the atmosphere (or equivalent altitude level) to the mole fractions determined by TMCA.	ASI/ MET	T and P time series	1 km and 5° attitude knowledge of montgolfière.
		I2: Assay the molecular complexity of the condensed phase.	**M2:** Chemical composition (elemental, molecular isotopic, and chiral) of aerosols	**A1:** Collect aerosols during their descent to the surface	TMCA	0–600 Da Mass spectra	1 km and 5° attitude knowledge of montgolfière
			M3: Chemical abundance of gases in troposphere	**A1:** *In situ* analysis of major and minor species	TMCA	0–600 Da Mass spectra	1 km and 5° attitude knowledge of montgolfière
			M4: Monitoring of T and P (T and P accuracy to 0.1 K and 1 mPa; and resolution to 0.02 K and 0.1% respectively) conditions to asses condensation status	**A1:** *In situ* measurements of T and P with reference to the altitude level	ASI/ MET	T and P time series	1 km and 5° attitude knowledge of montgolfière
		I3: Quantify the sources of chemical energy for atmospheric chemistry.	**M3:** Search for electric discharges	**A1:** Electric field and optical sensors	TEEP-B	Time series spectra	Coordinated with VISTA-B
			M4: Infrared spectra of relevant complex organics	**A1:** Identify organic species in the 5–5.6 μm wavelength range	BIS	Infrared maps of the surface between 1 and 5.6 μm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from Table 2.3-1, *Science traceability matrix: orbiter, and* Table 2.3-2, *Science traceability matrix: lake lander.*

Table 2.3-3. *Science traceability matrix: montgolfière, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATION	PLANNING MEASUREMENT APPROACH	PLAN. INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O1:** Determine the chemical pathways leading to formation of complex organics at all altitudes in the Titan atmosphere and their deposition on the surface.	**I4:** Determine surface composition.	**M3:** High spatial resolution (2.5 meters at 10 km) infrared spectra at wavelengths larger than 4.8 µm	**A1:** Identify organic species in the 5–5.6 µm wavelength range	BIS	Infrared maps of the surface between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
			M4: *In situ* sampling of surface organic inventory	**A1:** MS analysis of collected surface material	TMCA	Mass spectra	Surface composition measured when landing.
	O2: Characterize the degree to which the Titan organic inventory is different from known abiotic organic material in meteorites.	**I1:** Assay the composition of organic deposits exposed at the surface, including dunes, lakes, and seas.	**M5:** High-resolution images to detect organic materials	**A1:** Identify organic species in the 5–5.6 µm wavelength range	BIS	Infrared maps of the surface between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
				A2: Stereo images	VISTA-B	1360x1024 stereo images 48°FOV; digital terrain models	Precise location of montgolfière to 1 km and 5° attitude knowledge .
		I3: Determine the location and the composition of complex organics in and around impact craters in the equatorial regions.	**M1:** High-spatial resolution mapping of organics in areas such as impact craters and cryovolcanoes.	**A1:** High spatial resolution (2.5 meters at 10 km) infrared spectra at wavelengths between 5 and 6 µm	BIS	Infrared maps of the surface between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
				A2: High resolution color images	VISTA-B	1360x1024 multispectral images 48°FOV color albedo maps	Precise location of montgolfière tp 1 km and 5° attitude knowledge.
	O3: Characterize what chemical modification of organics occurs on the surface.	**I1:** Determine the roles of cratering and cryovolcanism in modification and hydrolysis of organics.	**M4:** Subsurface stratification of organics.	**A1:** Radar sounding of the subsurface at frequency between 150 and 200 MHz allowing a spatial resolution of a few hundred meters (500 m) and vertical resolution <6 m	TRS	Time series of radar profiles representing the sub-surface stratification	Precise identification of the trajectory of the montgolfière to 1 km and 5° attitude knowledge required.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from **Table 2.3-1**, *Science traceability matrix: orbiter, and* **Table 2.3-2**, *Science traceability matrix: lake lander.*

Table 2.3-3. *Science traceability matrix: montgolfière, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS/ DETERMINATION	PLANNING MEASUREMENT APPROACH	PLAN. INSTR.	DATA PRODUCTS	MISSION REQUIREMENTS
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O3:** Characterize what chemical modification of organics occurs on the surface.	**I2:** Determine the importance of surface inorganic compounds as surface catalysts or doping agents.	**M2:** Identify inorganic salts and compounds containing phosphorous and other potentially reactive inorganic agents in equatorial regions.	**A1:** Partially met with repeated near-IR mapping spectroscopy within the atmospheric transmission windows. High spatial resolution (2.5 m at 10 km) infrared mapping of the surface	BIS	Infrared maps of the surface between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
	O4: Characterize the complexity of species in the subsurface ocean.	**I1:** Determine whether evidence of sub-surface ocean species is present in cryovolcanic sites.	**M2:** Map compounds such as ammonia, sulfates, and more complex organics (e.g., CH_3COOH) at cryovolcanic sites	**A1:** Near-IR mapping spectroscopy within the atmospheric transmission windows with 2.5 m spatial resolution.	BIS	Infrared maps of the surface between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
	O5: Characterize bulk composition, sources of nitrogen and methane, and exchange between the surface and the interior.	**I1:** Determine whether carbon dioxide is primarily internally derived or photochemically produced.	**M3:** Profile of CO and CO^2 in the troposphere	**A1:** Infrared spectroscopy within the methane windows.	BIS	CO and CO^2 Profiles as a function of position and time.	Precise identification of the trajectory of the montgolfière to 1 km and 5° attitude knowledge required
		I2: Determine whether methane is primordial or derived from carbon dioxide.	**M5:** Map of surface CO_2 in the equatorial regions	**A1:** High spatial resolution (2.5 m at 10 km) infrared mapping of the surface.	BIS	Infrared maps of the surface between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
		I3: Determine whether molecular nitrogen is derived from ammonia.	**M5:** Detect ammonia in surface material: down to 1% in local deposits	**A1:** High spatial resolution (2.5 m at 10 km) infrared mapping of the surface	BIS	Infrared maps of the surface between 1 and 5.6 µm with a spectral sampling of 10.5 nm.	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
		I4: Determine whether pockets of partial melt are present at depth.	**M2:** Subsurface sounding at frequency between 150 and 200 MHz in order to detect liquid reservoirs less than 1 km deep.	**A1:** High resolution subsurface profiles over few hundred meters (500 m) spot size and vertical resolution <6 m	TRS	Time series of radar profiles representing the sub-surface interfaces	Precise location of the montgolfière makes it possible an integrated multiscale analysis of the TRS profiles with the radar measurements acquired by the sounder on the orbiter. Precise location of montgolfière to 1 km and 5° attitude knowledge.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is a continuation from Table 2.3-1, *Science traceability matrix: orbiter, and* Table 2.3-2, *Science traceability matrix: lake lander.*

2.4 Science Implementation

The TSSM Baseline mission comprises an orbiter, developed by NASA, which would provide accommodation for two ESA-provided Titan *in situ* elements; a montgolfière aerial platform that would provide global coverage over a six month prime mission from a nominal altitude of 10 km, and a battery powered (~9 hr nominal life) lander targeted to a northern hydrocarbon sea. A NASA-only science floor, defined as the orbiter alone, would give up *in situ* measurements from dedicated elements, but would retain the full set of orbital science investigations at Titan, as well as *in situ* atmospheric sampling through the aerobraking phase, detailed Enceladus science and Saturn system science during the tour phase.

In the Baseline mission, the orbiter would deliver the ESA elements to Titan, and provide data relay during their missions, prior to its own insertion into Titan orbit. During this Saturn Tour Phase, the orbiter would also collect detailed scientific data on Enceladus through seven close flybys (**Figure 2.4-1**).

Following the Saturn Tour Phase, the orbiter would capture revolutionary *in situ* science measurements by dipping deep into Titan's atmosphere during a two month Aerobraking Phase. Once in Titan's orbit the NASA orbiter would provide full global coverage of Titan with a rich complement of instruments from a 1500 km circular orbit over a nominal duration of 20 months.

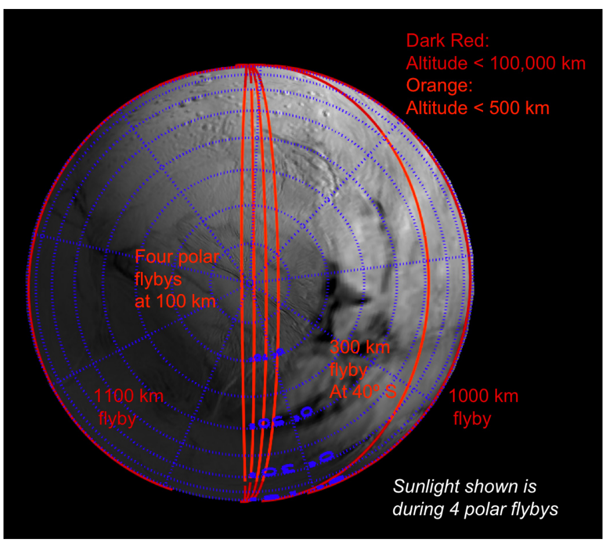


Figure 2.4-1. *Schematic representation of the seven close (100 km to 1100 km) and two distant (20,000 km to 30,000 km) Enceladus flybys. The four over the pole are at 100 km; the one at 40°S is at 300 km. The two equatorial flybys are at ~1000 km. The distant flybys are both at ~20°N. Flybys can be targeted to go through vent locations, if desired.*

The JSDT determined that the orbiter instruments were not to be considered descope elements at this stage. This is because the planning payload was designed to provide a focused instrument suite on the orbiter and allow for accommodation of the full suite of ESA *in situ* elements. The instrument suite covers science investigations spatially, ranging from the deep interior of Titan to the far reaches of the atmosphere. Non-science descope options have been identified and are discussed in detail in §4.11.7.8.

The flight elements shown in **Figure 2.4-2** would be launched on an Atlas V 551 launch vehicle in 2020 using a gravity assist solar electric propulsion (SEP) trajectory to achieve a trip time of 9 years to Saturn. Following Saturn Orbit Insertion, the orbiter would conduct a Saturn system tour, including seven Enceladus flybys (four over the poles at 100 km, one at 300 km and two at 1000 km) and 16 Titan flybys. This phase will allow excellent opportunities to observe Saturn, multiple icy moons (including Titan), and the complex interaction between Titan and Saturn's magnetosphere. The montgolfière balloon would be released on the first Titan flyby and use an X-band relay link with the orbiter for communication during critical events and during its prime mission. The lander would be released on the second Titan flyby and use a similar communication scheme. This 24 month period will also mark the mission phase when the majority (if not all) of the Titan *in situ* data is relayed back to Earth. Following its tour of the Saturn system, the orbiter would enter into a highly elliptical orbit to conduct a two-month concurrent aerobraking and aerosampling phase in Titan's atmosphere, where it would dip as low as 600 km from Titan's surface. The orbiter would then execute a final periapsis raise burn to achieve a 1500 km circular, 85° polar-mapping orbit. This Circular Orbit Phase will last 20 months.

On completion of the mission, a Decommissioning and Disposal Phase would be

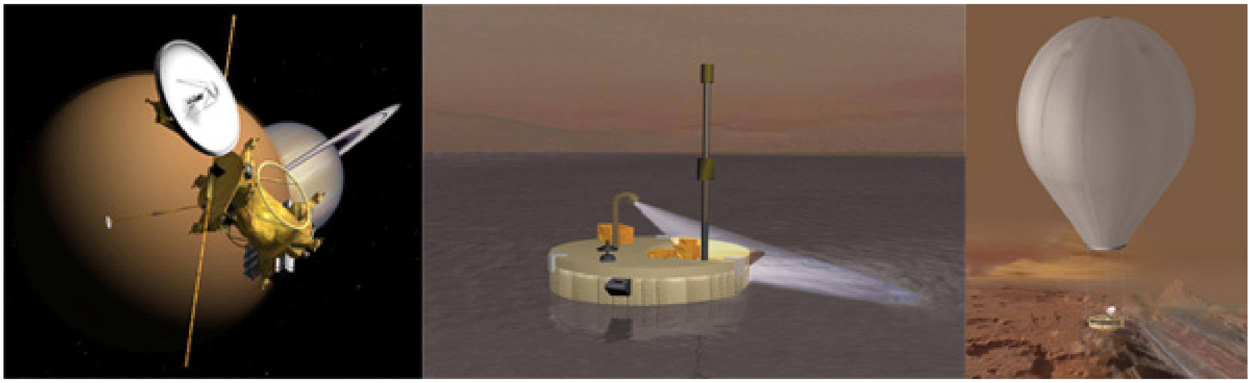


Figure 2.4-2. The Baseline mission elements accomplish comprehensive scientific exploration of Titan and Enceladus.

initiated by a maneuver that would start the orbit decay assisted by the influence of Saturn perturbations and Titan's atmospheric drag with a targeted impact to ensure planetary protection requirements are met. Although not in the current plan, there would be extraordinary opportunities for atmospheric, magnetospheric and surface science during this phase.

The orbiter concept carries a mass allocation of 165 kg for its remote sensing instruments and an allocation of 830 kg for ESA provided *in situ* elements. The flight and ground systems are sized to provide the data volumes necessary to return measurement data from the orbiter and *in situ* elements.

The JSDT looked across the *in situ* elements and the orbiter in determining the planning payload in order not to duplicate measurements and to ensure synergy *between* the elements. For example, it was determined that the most exciting scientific result from the lake lander would be a chemical analysis of the lake and species dissolved in the lake (§2.6). Thus, the focus of the lander instruments is high resolution chemical analysis with supporting instrumentation to understand the context for those measurements. This type of chemical analysis was then not duplicated on the montgolfière or the orbiter, but rather complemented by a lower resolution aerosol chemical analysis on the montgolfière and gas phase ion and neutral species analysis on the orbiter.

The instruments selected for the planning payload on the orbiter are described in §2.4.2 and §2.4.3. These sections outline how this specific suite of instruments meets the measurement requirements and how they therefore fulfill the science investigations. The planning payload for the *in situ* elements is also listed in §2.4.10, although they are not described in detail as they are ESA's responsibility. More information on these specific instruments is given in Appendix J.

2.4.1 Payload Considerations

The planning scientific payload described in this section is a direct outcome of the scientific investigations deemed critical by the JSDT. Developing a planning scientific payload for a planetary mission required the JSDT to consider both of scientific goals and the objectives laid out by the National Academy and/or results from previous missions. From the scientific investigations, the JSDT developed measurement requirements, §2.3.6, which led to measurement approaches. The approaches are not unique in that a variety of instruments in differing combinations could achieve the measurement requirements.

Consideration was also given to the potential for serendipitous discovery. Discovery-based science is well-illustrated by the Cassini orbiter's discovery and then follow-up analysis of the active plumes on Enceladus. A wide range of different techniques were brought to bear on the plumes once discovered by the Cassini magnetometer, enabling a complete characterization that has over-turned our understanding of the evolution of icy bodies and provided key chemical information on the nature of the Saturnian satellites.

In creating the planning payload for TSSM, the JSDT has derived a robust set of model instruments that addresses specific measurements to test known hypotheses, while provid-

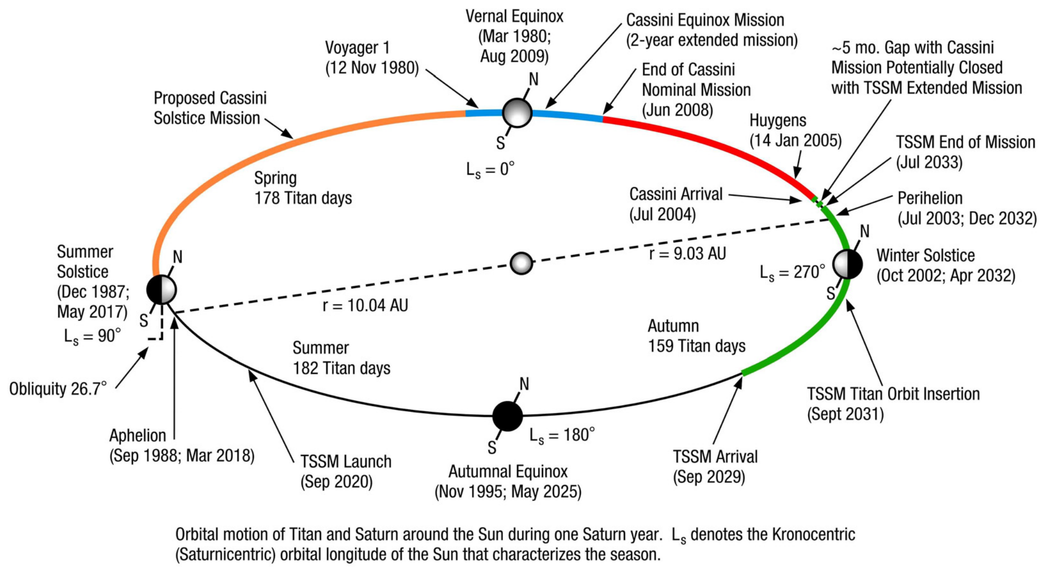


Figure 2.4-3. *Expected phasing of TSSM mission is complementary to Cassini-Huygens.*

ing a broad and highly capable instrument suite that allows the flexibility to respond to new discoveries. The JSDT also took into consideration the arrival time at Titan which corresponds to a seasonal phase complementary to the existing Cassini mission. **Figure 2.4-3** shows TSSM's expected mission duration and the seasonal complementarity.

2.4.2 Planning Payload

Measurement requirements of §2.3 can be traced to a mission planning payload of six instruments (exclusive of the telecom system, which supports radio science). This planning payload was used to allow the scientists and engineers to develop a complete mission concept that addressed the identified science objectives within a reasonable set of requirements and constraints. In addition, the planning payload enables engineers to understand what requirements are imposed by different payload elements. However, there are other combinations of instruments that could achieve similar scientific results. For example, possible instrument pairings one can consider to better understand Titan's atmosphere are the instruments chosen in this study (Thermal Infrared Spectrometer (TIRS) and Sub-Millimeter Spectrometer [SMS]), but a TIRS or a SMS and a solar occultation FTIR instrument could also provide high detection sensitivity for trace organic composition and global temperature fields and direct measurement of winds.

The actual instruments would be the result of an Announcement of Opportunity (AO) selection process carried out by NASA. Consequently, the instruments discussed in this section should be taken to be neither the final selections nor the final implementations of the orbiter instruments. These instruments do, however, meet the measurement requirements while remaining within the available resources and with minimal technical and programmatic risk. These instruments cited are all within the state of the art and all have strong flight heritage. Through their existence, these planning-payload instruments validate the science measurement requirements.

Similarly, knowledgeable and creditable instrument descopes cannot be made until after the flight instruments have been selected (i.e., have become known quantities). Thus, the inclusion of instruments in the descope matrix will be done after they have been selected. Accordingly, the TSSM descope options identified now focus on spacecraft and mission systems and capability. Furthermore, the deletion of an instrument is a last resort, not to be taken until after other options have been exhausted. This approach toward descopes is aligned with the philosophy of senior NASA management as espoused and discussed at a recent Annapolis workshop (NASA Academy

Table 2.4-1. Orbiter planning science instruments and instrument capabilities.

	Planning Science Instruments	Instrument Capabilities
HiRIS	High-Resolution Imager and Spectrometer (near IR)	Global surface mapping at 50 m/pixel in three colors (~2.0, 2.7, and 5–6 μm). Two spectral mapping bands 0.85 to 2.4 μm (5nm spectral resolution) and 4.8 to 5.8 μm supporting surface/atmosphere studies
TiPRA	Titan Penetrating Radar and Altimeter	>20 MHz global mapping of subsurface reflectors with 10 m height resolution in altimetry mode and better than 10 m in depth resolution. Lower data rate depth sounding mode with ~100 m depth resolution. Approximately 1km x 10 km spatial resolution.
PMS	Polymer Mass Spectrometer	Upper atmospheric *in situ* analysis of gases and aerosol precursors—M/ΔM ~10,000 for masses up to 10,000 Da. Focus instrument for aerosampling down to 600 km. Better than 10^4 particles/cm^3
SMS	Sub-Millimeter Spectrometer	Direct winds from Doppler and temperature mapping from ~200–1000 km altitude; CO, H_2O, nitrile and hydrocarbon profiles; heterodyne spectrometer with scanned mirror.
TIRS	Thermal Infrared Spectrometer	Organic gas abundance, aerosol opacity and temperature mapping 30–500 km. Passively cooled Fourier Spectrometer 7–333 μm. Spectral resolution 0.125-15 cm^{-1}.
MAPP	Magnetometer	Interaction of field with ionosphere: internal and induced field.
	Energetic Particle Spectrometer	Magnetospheric particle fluxes, ~10 keV to >MeV with 150° x 15° FOV.
	Langmuir Probe	Swept voltage/current probe. *In situ* electron density and temperature, ion speed constraint, including during aerosampling.
	Plasma Spectrometer	Electrostatic analyzer system, with a linear electric field (LEF) time-of-flight mass spectrometer. Measures ion and electron fluxes at few eV to a few keV. M/ΔM~10.
RSA	Radio Science and Accelerometer	Lower stratosphere and troposphere temperature profile. Gravity field. Mass and power are zero because all hardware components are part of the spacecraft bus: USO, UST, and accelerometers.

of Program/Project and Engineering Leadership's Knowledge Sharing Initiative 2008).

The payload consists of seven individual experiments, including remote sensing instruments, an *in situ* chemical analyzer, and a set of space physics instruments. In addition, the telecommunications system provides: 1) tracking data for accurate orbit reconstruction in support of geophysical objectives; and 2) RF occultation-intensity data to support of atmosphere studies.

Measurement approaches that the JSDT took to accomplish the measurement requirements are given in the orbiter Science Traceability Matrix (**Table 2.3-1**) together with the planning payload instruments and any identified mission requirements. The planning payload is also listed in **Table 2.4-1**, along with the capabilities that each instrument requires to meet the measurement goals cited in the Science Traceability Matrix. These instruments are described in detail in §4.2.

2.4.3 Measurement Approaches and Implementation

Following definition of measurement requirements, a wide variety of measurement approaches were evaluated extensively by the JSDT. It is too lengthy to discuss the instrument trades in detail, but the JSDT made sure that the measurement approach of every instrument met the relevant measurement requirement. This section provides a discussion of the planning payload model instruments that resulted from those discussions and fulfill the measurement requirements listed in the orbiter Traceability Matrix (**Table 2.3-1**) and discussed in §2.3.6.

2.4.3.1 High-Resolution Imager and Spectrometer (HiRIS)

High resolution imaging and identification of surface chemical features on Titan can be achieved by a combination of near-infrared (NIR) mapping spectroscopy and higher spatial resolution multispectral imaging. NIR spectroscopy has proven to be a valuable remote sensing tool in determining a broad range of properties planetary surfaces and atmospheres, including composition, physical properties (e.g., state, particle size), thermal properties, and geology. Most molecules have fundamental, overtone, and/or combination vibrations in the NIR, allowing their identification with NIR spectroscopy, provided sufficient spectral resolution (minimally $\lambda/\Delta\lambda$ > few hundred). Building 2-D images from spectra, as done by the Galileo Near Infrared Mapping Spectrometer and Cassini Visual and Infrared Mapping Spectrometer (VIMS), provides additional value in interpreting the geology of planetary surfaces as well as the structure of planetary atmospheres. In addition to a mapping spectrometer, a higher spatial resolution multispectral imaging system essen-

tial for elucidating active and ancient geologic processes operating on the surface is necessary. Such imaging, acquired in stereo, adds an invaluable third dimension that combined with NIR spectral maps will provide a potent combination for unraveling Titan's surface composition, history, and processes active today.

One example instrument is the High-Resolution Imager and Spectrometer (HiRIS) composed of both a near-IR camera and a near-IR spectrometer, which will be the first near-IR camera and spectrometer specifically designed to investigate the geology and map the composition of the surface of Titan. The measurement requirements placed on this instrument are, for the imaging system, a spatial resolution <50 m in at least three colors, and for the spectrometer, a spatial resolution <250 m, a spectral range from 0.85 –2.4 µm and 4.8–5.8 µm, and a spectral resolution, $\lambda/\Delta\lambda \sim 400$–500. The following section details the motivation behind each of these requirements and their significance on the engineering design.

The camera spatial-resolution requirement stems from a desire to improve by at least an order of magnitude, the resolution achieved by the Cassini Synthetic Aperture Radar. Such benchmarks are common practice in space exploration, and this improvement in the data will afford an entirely new perspective on the geologic processes acting on the surface of Titan. The JSDT examined the idea of again using radar to obtain images over Titan's entire surface at 50 m spatial resolution. Because of the way imaging radar works, including the strong distance penalty associated with transmitting the illuminating radio waves as well as receiving them (distance to the fourth power instead of distance squared), it was recognized early on that such a radar in a 1500 km orbit (even a 1000 km orbit, the smallest practicable) would be prohibitively expensive in mass, power, and data processing/volume requirements. Much higher signal-to-noise can be achieved by an imaging spectrometer than was possible with Cassini VIMS, which was not designed to observe Titan in this manner. Improvements in near-infrared detectors since the design of VIMS, optimization of the choice of wavelength range, and a larger aperture all combine to make high signal-to-noise imaging at near-IR wavelengths, 50 m spatial resolution

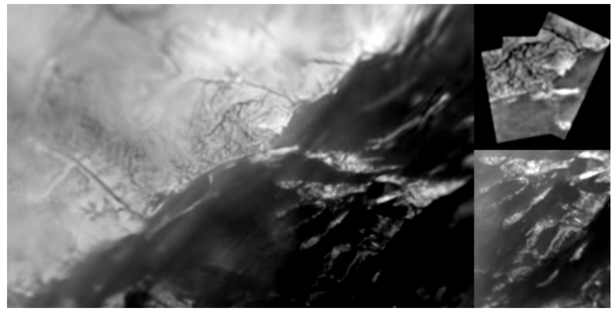


Figure 2.4-4. Mosaic of images from the DISR camera degraded to HiRIS resolution from orbit of 50 m/pixel. Note fluvial channels.

and global coverage feasible. **Figure 2.4-4**, a mosaic of DISR images degraded to a resolution of 50 m/pixel (i.e., the spatial resolution of HiRIS), demonstrates the scientific value these data will provide.

The desire for some gross compositional information at the resolution of the camera drives the requirement for color images (a minimum of three colors). The hazy methane-rich atmosphere of Titan provides challenges in meeting these requirements, but it can be done. Imaging the surface in visible to near-IR light is only possible through discrete transmission windows (Griffith et al. 1991, 2003). Scattering by aerosols in the atmosphere affects seeing through the atmosphere across the spectrum, with more pronounced scattering at shorter wavelengths and decreased scattering at longer wavelengths (Smith et al. 1981, 1982; Tomasko et al. 2005).

The 2.0, 2.7, and 5 µm transmission windows have been selected for imaging as they represent a range of compromises between scattering by aerosols in the Titan atmosphere and solar irradiance. Both the 2 and 5 µm windows are relatively transparent to the gasses in Titan's atmosphere (**Figure 2.4-5**). The 5 µm window is advantageous because it is subject to less scattering by aerosols, which falls of as $1/\lambda^4$ for λ greater than a few µm, while the 2 µm window benefits from the increase in available solar irradiance. While the 2.7 µm window is slightly less transparent than the 2 and 5 µm windows, it is more advantageous than the shorter-wavelength 1.0, 1.3, or 1.6 µm windows as scattering at these short wavelengths will limit the spatial resolution (the maximum resolution the Cassini Imaging Science Subsystem achieves at Titan

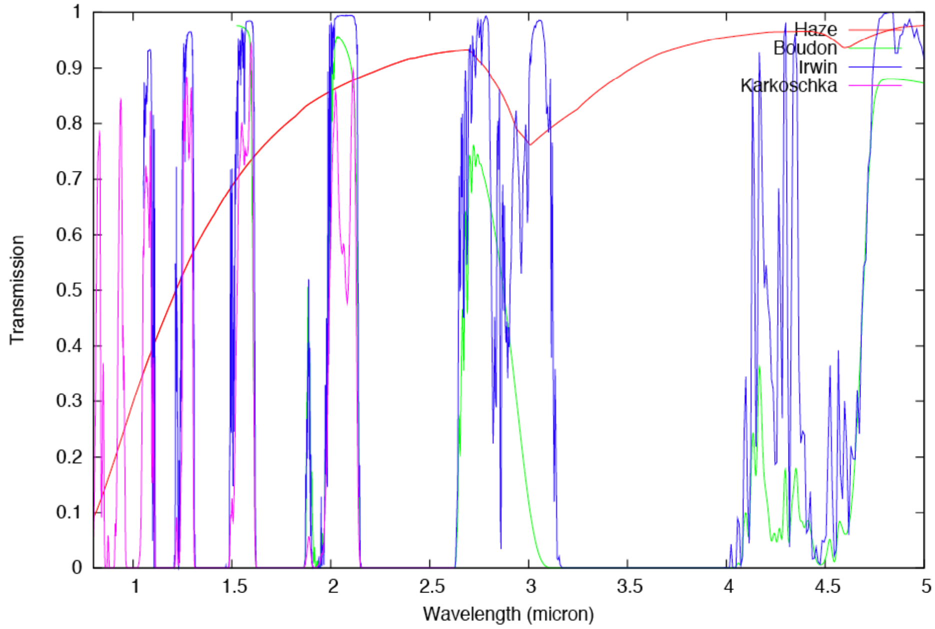


Figure 2.4-5. *Transmission through Titan's atmosphere versus wavelength in µm. Results from different data sets are shown but the blue line gives overall transmission through the gas, and red line transmission through the haze. A clear atmosphere has a transmission of 1. Note that in the 5 µm window the atmosphere is clear, and even in the 2 µm window the haze does not impede observation of the surface. Although the calculations were not done up to 5.8 µm, the window continues to be as transparent from 5–5.6 µm as it is at 5 µm. Model calculations from Cassini and other data by Alberto Negrao.*

is ~1 km in the 0.94 µm window). A large aperture is required to provide an adequate signal-to-noise ratio (SNR), particularly in the 5 µm window where the solar irradiance is down significantly.

The spatial resolution specified for the spectrometer (250 m/pixel) represents a compromise between spatial resolution, data volume, and instrument mass. Both the Cassini Visible and Infrared Mapping Spectrometer (VIMS) and SAR instruments have identified a broad range of geologic structures in data with spatial resolutions >0.25 km (e.g., Elachi et al. 2005, 2006; Sotin et al. 2005; Barnes et al. 2006, 2007a; Stofan et al. 2006, 2007; Lopes et al. 2007; Radebaugh et al. 2007, 2008; Soderblom et al. 2007; Brown et al. 2008; Lorenz et al. 2008b; Lunine et al. 2008) for which compositional information is limited at best. This increase in spatial resolution over VIMS reduces linear mixing in the data affording greater sensitivity in identifying minor constituents.

Like the imager, the spectral range of the spectrometer is determined by absorption and scattering in Titan's atmosphere. The specified spectral range can be broken into three parts: 4.8–5.8 µm, 1.9–2.2 µm, and 0.85–1.75 µm. The 4.8–5.8 µm region, only partially sampled by VIMS, represents an ideal spectral range in which to study the surface of Titan; this region of the spectrum is highly diagnostic for many materials, including many hydrocarbons (see **Figure 2.4-6**; cf. Clark et al. 2008b), and, as discussed above for the imager, scattering and absorption by the atmosphere are minimal. The second spectral region we've identified, the 2 µm window, has proven to be one of the most fruitful single windows for analyzing VIMS data (e.g., Soderblom et al. 2007; Brown et al. 2008; McCord et al. 2008). The 1.9–2.2 µm region also includes the feature at 2.21 µm used by ground-based observers to tentatively identify ammonia on the surface of Enceladus and other Saturnian satellites (Verbiscer et al. 2006, 2008); HiRIS will be able to test this identification and provide a spatially resolved map of the location of ammonia on Enceladus and whether it is (as one presumes but does not know) associated with the

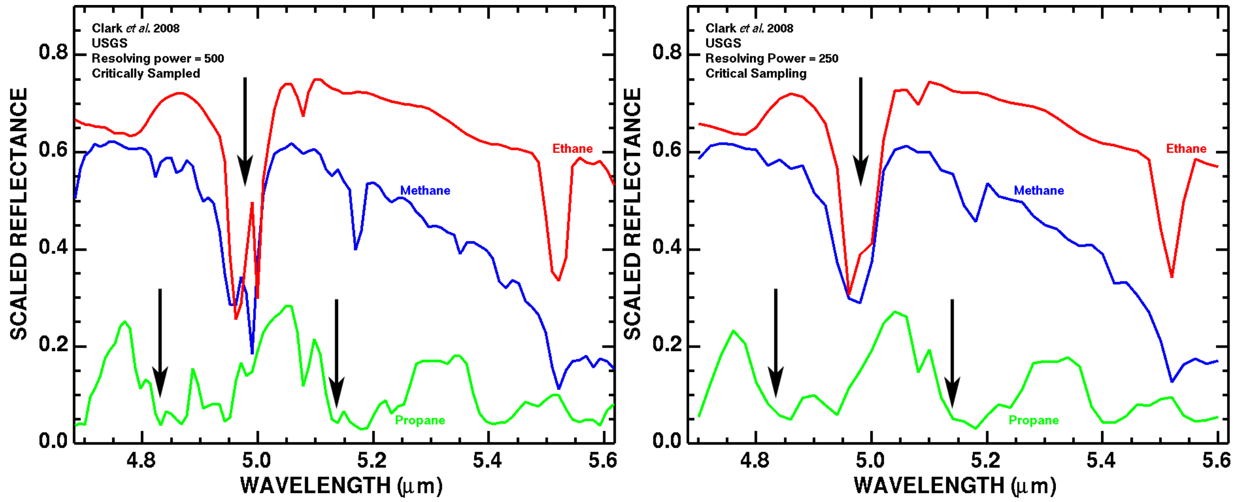


Figure 2.4-6. Spectra of liquid hydrocarbons that are known or suspected to be on the surface of Titan sampled at two spectral resolutions (number of data points per wavelength). In the left frame, the resolution is 10 nanometers, which is that proposed for HiRIS while the right frame shows a factor of two coarser resolution, corresponding to the Cassini VIMS instrument. Note the clear difference (arrows) between the spectra of methane (blue line) and ethane red line) in the 4.9 to 5.0 μm range in the left plot that are not evident in the right plot. Because the lakes are largely ethane-methane, HiRIS provides a constraint on their ratio unavailable from Cassini VIMS. (Figure provided by Roger Clark, USGS.)

plumes. The third spectral range, from 0.85–1.75 μm, is included to sample four atmospheric transmission windows that collectively have been used to provide additional leverage on constraining the composition of the surface and atmosphere (e.g., Griffith et al. 1991, 2003; Coustenis et al. 1995, 2005; Tomasko et al. 2005; Barnes et al. 2006, 2007b; Soderblom et al. 2007; McCord et al. 2008). This window contains a 1.6 μm ammonia feature which, together with features beyond five μm, will allow a much more sensitive search for ammonia on Titan's surface than was possible with VIMS. In addition to the atmospheric windows, the wings of the atmospheric transmission windows, which allow us to characterize and correct for the atmosphere in these data, have been included in these spectral ranges.

The 5–6 μm region is a new part of the spectrum hitherto unseen on Titan, which contains a wonderful set of diagnostic absorption features for a range of organic molecules. This region also represents the best window with respect to scattering for reflectance spectroscopy. Extending the range of the spectrometer to 7 μm was explored, but it increased the complexity and/or reduced the spectral range at the short wavelength cut-off.

VIMS was not designed for use at Titan and the efficiency of the instrument is quite low at 5 μm (on order of 1–2%). In contrast, HiRIS's capabilities will enable the diagnosis of major hydrocarbon components of the southern hemisphere lakes, like Ontario Lacus, (which will not be visited by the lake lander or montgolfière). It will also provide a global map of the composition of the nitrogen-bearing organics, or nitriles, and make other discoveries of materials as yet unknown.

The science required of the spectrometer, specifically to identify a range of organic and inorganic compounds, drives the requirements on the spectral resolution. In order to reliably discriminate between many of these compounds, a spectral resolution on order 500:1 is required (see **Figure 2.4-6**). With more realistic mixtures of ices, the increase in spectral resolution over VIMS allows non-linear mixing.

In order to achieve sufficient SNR for the spectrometer given such high spectral and spatial resolutions, the spectrometer makes use of a 10× image motion compensation mirror, allowing integration times of up to ~2.7 s.

Allowing one pixel of smear due to pointing instability during this integration time, a pointing stability of <60 μrad/s is required, which is well within the spacecraft capability.

HiRIS Signal- to-Noise Analysis

Some straightforward calculations and comparison with VIMS actual imaging performance can be used to demonstrate that HiRIS camera will meet its SNR and spatial resolution requirements with confidence. The signal from the HiRIS camera can be written as

$$S = \int_0^t \int_{\lambda_1}^{\lambda_2} E \cdot a \cdot T \cdot Q \cdot N(\lambda) \cdot C \; d\lambda \; dt'$$

where

- E = optics solid angle, 0.06 sr for f/3.6 optics
- a = pixel area, 3.24×10^{-6} cm^2 for an 18 μm pixel
- T = optics transmission, 0.5 (typical)
- Q = detector quantum efficiency, 0.7 e^-/photon (typical)
- N = scene radiance = $\Phi(\theta)$ A I/(π d^2) (erg/s/cm^2/μm/sr)
- $\Phi(\theta)$ = surface photometric function, ~1 at subsolar point
- A = surface albedo, ~0.05 for Titan at 5 μm (from Cassini VIMS observations)
- I = solar irradiance at 1 AU in erg/s/cm^2/μm
- d = distance from the sun in AU, ~9.5 AU for Titan
- C = conversion constant from erg to photons, ~2.5×10^{12} photon/erg at 5 μm
- t = integration time, 53 ms (1 pixel of smear for a 1,500 km altitude orbit)
- λ_1 and λ_2 = bandpass limits, 4.9 and 5.8 μm respectively

Performing this integral yields a total signal of ~16,500 e^- for a 2 × 2 binned pixel thereby yielding a SNR ~130 for a 50 m/pixel image of Titan at 5 μm from 1500 km at the subsolar point assuming the instrument is shot noise dominated.

A comparison with actual VIMS performance confirms this result. VIMS data are used to construct 5 μm images of Titan's surface by co-adding spectral channels from ~4.9–5.2 μm. These co-added images typically achieve a SNR ~10–20, which includes all effects from Titan's atmosphere (Brown 2008). **Table 2.4-2** compares the VIMS and HiRIS system parameters. The HiRIS signal will increase relative to VIMS, as the product of the ratio of the system throughputs, the effective bandpasses, the square of the angular resolutions, and the square of the front optics sizes. While VIMS is read-noise dominated, HiRIS will be shot-noise dominated, as such the total noise for HiRIS might be a factor of a few higher than its read noise. Thus, the HiRIS noise will decrease relative to VIMS, as the ratio of the read noises divided by a factor of a few (a factor of four is assumed for this calculation). Using the performance characteristics of VIMS and HiRIS, and the SNR achieved by VIMS at 5 μm, the SNR of HiRIS can be estimated as SNR_{HiRIS} ~80–160 for a 50 m/pixel image of Titan at 5 μm, entirely consistent with the calculation above.

***Table 2.4-2.** HiRIS system parameters vastly improve on VIMS performance.*

	Total Throughput	5-μm Bandpass	Angular Res	Front Optics	Read Noise
VIMS	0.015	0.3 μm	0.5 mrad	23 cm	1500 e^-
HiRIS	0.35	0.9 μm	0.033 mrad	30 cm	25 e^-

Atmospheric scattering will have minimal effect on spatial resolution of HiRIS images. Cassini ISS is limited to ~1 km resolution at 1 μm. Atmospheric scattering decreases as $1/\lambda^2$–$1/\lambda^4$ for λ > a few μm. Thus, the scattering-limit maximum resolution for an imager at 5 μm is on order 10 m compared to the HiRIS pixel footprint of 50 m. Attenuation by methane in the Titan atmosphere should be <0.5 in the 5 μm window.

Figure 2.4-7 illustrates the SNR calculated for the HiRIS spectrometer at 10 nm spectral resolution with its nominal 2 × 2 pixel binning and using its image-motion-compensation mirror to increase the effective integration time. The expected SNR for HiRIS, including more specific details regarding operation of the instrument, is discussed further in §4.2.2.1. This section also includes a more detailed discussion of the SNR calculated for the HiRIS camera and spectrometer during the Enceladus encounters.

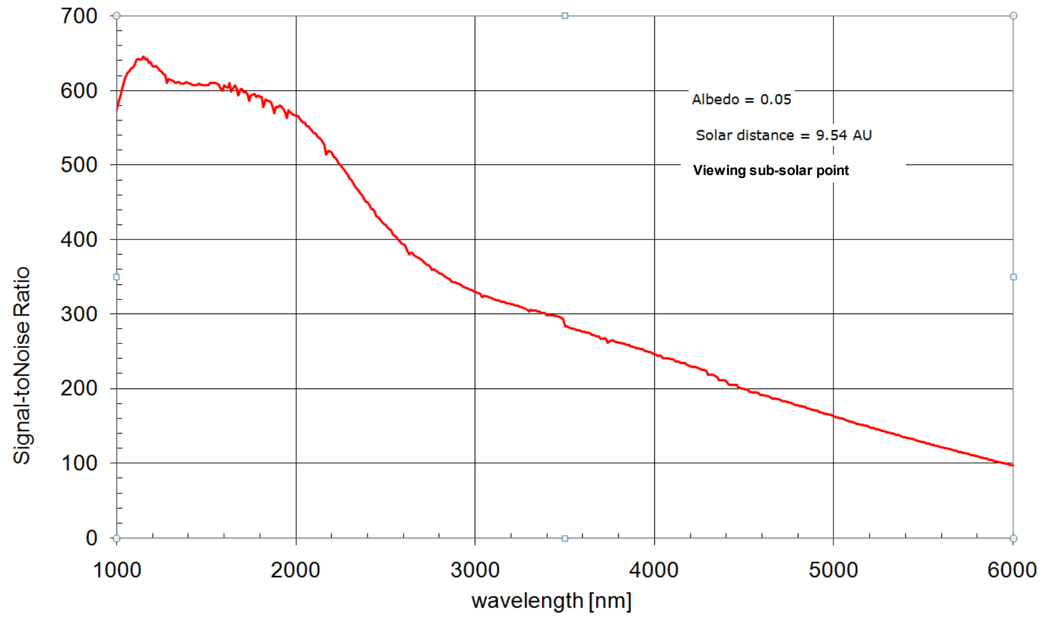


***Figure 2.4-7.** HiRIS will provide excellent SNR at Titan over its entire spectral range.*

2.4.3.2 Titan Penetrating Radar (TiPRA)

Many of the science investigations and measurement requirements are fulfilled by surface topography and subsurface sounding. Radar measurements have been successfully used to provide excellent quantitative data on Mars and Titan For example, SHARAD on MRO probes the subsurface using radar waves within a 15 to 25 MHz frequency band to get the desired, high-depth resolution. The radar wave return, which is captured by the SHARAD antenna, is sensitive to changes in the electrical reflection characteristics of different materials, including any water that may be present in the surface and subsurface. Water, like high-density rock, is highly reflective. Changes in the reflection characteristics of the subsurface, caused by layers deposited by geological processes in the ancient history a planetary body, are also visible.

For Titan, the measurement requirements are different because of the nature of Titan's surface and the 1500 km altitude that the orbiter will maintain. There are three sets of driving requirements for this specific Titan Penetrating Radar instrument: 1) altimetry measurements at Titan with a vertical resolution better than 10 m, a spatial resolution (along-track) of 1–2 km, and a footprint of 1–10 km; 2) subsurface sounding at Titan with a vertical resolution better than 10 m, a spatial resolution better than 10 km, and a penetration depth of up to 5 km; and 3) subsurface sounding at Enceladus with a vertical resolution better than 10 m, a spatial resolution up to 1 km, and a penetration depth up to 50 km. The driving science requirements are given in the previous section and in the Traceability Matrix, **Table 2.3-1**.

Radar observations at Enceladus and then Titan can be achieved with the same subsystems onboard the spacecraft, but using a dedicated antenna at Enceladus. TiPRA measurement requirements at Enceladus are set by the objective to characterize the subsurface at the south pole, and especially to detect shallow liquid water in that area. In colder areas, increased penetration depth will provide key constraints on Enceladus' global geophysical history.

High-resolution topography of morphological features with a footprint of 1–10 km will help understand geological processes shaping Titan's surface: large near-equatorial basins and highlands, erosional features such as channels, dendritic valley networks, fluvial erosional deltas, and possible glacial-flow features, volcano-tectonic features such as domes, cryovolcanic flows, and bright spots (e.g., Tui Regio, Hotei Regio), slope and roughness of impact craters and other sub-

circular features, topography, slope and roughness of depressions where former lakes may have been present. A resolution up to 0.5 km (along-track) will also enable better imaging of the widespread aeolian, erosional and depositional features such as dunes.

A footprint better than 10 km is also necessary to increase the understanding of atmospheric circulation on a regional scale (relative humidity, winds, temperature profile) in near-equatorial environments and the relationship between topography and meteorology on a regional scale (drizzle, rainstorm, hail and cloud formation) in near-equatorial environments.

The altimetry map will be used for correcting the gravity measurements in order to identify lateral variations in density, thereby providing additional information on the compensation state of near-equatorial geologic features on a regional scale (e.g., Xanadu).

The envisioned TiPRA configuration will also enable topography measurements with a spatial resolution up to 0.5 km (along-track) and a footprint of 1 km, which will be used for developing three-dimensional images of Enceladus' subsurface.

Radar penetration depth is a function of the probed material and observation altitude, as discussed below. However, it is envisioned that a penetration depth of up to 5 km at Titan and up to 50 km at the coldest areas on Enceladus can be achieved. These measurements will provide constraints on the geological and compositional stratification at these satellites.

The three-dimensional imaging resolution of TiPRA at Titan is necessary for characterizing shallow subsurface units at a relatively high resolution. Two geometrical aspects are to be considered. The spatial resolution and penetration depth will enable the detection of geological units, such as sedimentary basins, lakes, cryo-volcanic flows. The vertical resolution will enable the characterization of stratigraphic relationships with relations between different units and the discontinuities. These structures will be correlated with the surface morphology. A penetration depth of up to 5 km could even allow the detection of liquid water or partial melt in the icy crust if it happens to be in a few kilometers below the surface (e.g., Tobie et al. 2006; Nelson et al. 2008).

TiPRA observations at Enceladus' south pole will provide constraints on geological horizons, e.g., due to cryovolcanic ejecta, geological surfaces buried as a result of global or regional resurfacing. High-resolution stratigraphy will provide constraints on the geometry of volcanic deposits around the tiger stripes. High penetration depth will provide constraints on successive surfaces (i.e., due to successive resurfacing) and the nature of the subsurface below the tiger stripes. Several very different models are currently proposed to explain the intense geology at Enceladus' south pole. Models indicate that liquid water could be present a few meters (Spencer et al. 2006) to a few kilometers below the surface (e.g., Nimmo et al. 2007).

The penetration depth expected for TiPRA is primarily a function of the observation altitude as well as the nature and temperature of the sounded terrains. Penetration depth is estimated from observations at terrestrial analogs and experience gained from measurements at Mars (e.g., Lorenz et al 2008c). Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) aboard the European Mars Express spacecraft has measured very low attenuation within the Mars polar ice, although Mars polar ice is believed to contain up to 20% non-ice impurities. The primary reason for low bulk attenuation is the cold temperature of the ice. Both Antarctica and Mars polar caps are relevant analogs to Titan's and Enceladus' subsurface because they associate water-ice and clathrate hydrates, which are predicted to be major constituents of both Titan's and Enceladus' icy shells (e.g., Tobie et al. 2006; Kiefer et al. 2006; Fortes 2007). On the other hand, limited knowledge of Titan's surface composition and structure, e.g., porosity at various scales, precludes a firm prediction of the penetration depth that will be achieved by TiPRA at this satellite. Ground-penetrating radar investigation at terrestrial ice sheets for the same range of frequencies considered for TiPRA (mean frequency and bandwidth of a few tens MHz) have reached depths of up to 3 km (e.g., Studinger et al. 2003; Holt et al. 2006). SHARAD's observations have achieved penetration depths of 0.1 km (in porous regolith) to more than 2.5 km at Mars' north polar layered terrains with demonstrated capability to see deeper. The very low tem-

peratures (i.e., <200 K) at the Saturnian satellites will enhance the transparency of the material and the radar signal penetration. Based on these results and the expected cold ice temperature expected at both Titan and Enceladus the radar is capable of detecting horizons as deep as many tens of kilometers. Although nobody can ensure the maximum allowed penetration based on possible volumetric scattering, it is prudent to design the radar such that it will not preclude the investigation of deep horizons under cold Enceladus or Titan surface.

The mean frequency suggested in the present document, i.e., >20 MHz, is representative of the range of frequencies that can achieve the required spatial resolution of a few kilometers as well as subsurface sounding a few kilometers deep. The SHARAD instrument (SHAllow RADar on Mars Reconnaissance Orbiter) has been used as a reference for assessing the science return expected at Titan from TiPRA. The instantaneous bandwidth equal or greater than 10 MHz will yield a vertical altimetry resolution of 10 m and will allow the resolution of horizons in Titan's and Enceladus' crusts with the same level of accuracy.

Panel 2 in **Figure 2.4-8** shows an actual SHARAD radargram over the north pole of Mars with panel 1 showing the ground track (200 km wide and more than 1000 km long) with associated modeled radargram (shown in panel 2) based on available MOLA topography and spacecraft ephemeris. The other two images in panels 4 and 5 show modeled radargrams over the same track but at altitudes of 1000 and 1500 km respectively. As expected, a higher clutter signature is seen from the rougher areas in the two models at 1000 and 1500 km altitudes. However, the models also demonstrate that at 1500 km altitude, there is a clear detection of the surface that will allow altimetry equally well at all these altitudes. The pass includes both smooth (~1 m r.m.s height within 5 km box) and rough areas with sand dunes with r.m.s. height of ~10 m. **Figure 2.4-9** zooms into the yellow box in **Figure 2.4-8** and shows the detailed difference in radar signature between the low and high roughness regions. **Figure 2.4-10** shows a high-resolution CTX image of the sand dune region. These sand dunes have a more random geometry than the ones expected at Titan and consequently the TiPRA coherence loss over Titan dunes will be less. Both coherent and incoherent cross-track clutter are observed in the data; but the models, due to a lack of sufficient resolution in the MOLA topography, only capture the coherent clutter signatures. A similar difference in Titan is also expected. Also, the coherent return from the surface shows a SHARAD-type instrument capability's to sound the subsurface at higher altitudes. The biggest difference in the performance as a function of altitude is the reduced single echo power due to increased range. Our design can overcome this by a combination of onboard processing and an increase in radar transmit power from 10 W to 100 W.

As shown in the above models, an increase in the altitude will increase the level of surface clutter over rough regions (e.g., sand dunes). Although this would constitute a limitation during data interpretation, TiPRA will still provide unambiguous data over many smooth surfaces on Titan such as lakes and smooth non-dune regions. This is evident by looking at the layered portion of the track where there are clutter signatures but they do not prohibit the interpretation of the data as a stratified medium under the NPLD. Also, on Enceladus some of the deep returns will not be confused with surface clutter which is stronger at near range. Even in areas of high clutter, there are techniques that use parallel tracks to discriminate between surface clutter and depth return. Finally, the level of loss in the signal coherence due to roughness is not only a function of the surface rms height but also a function of dielectric contrast between the two mediums.

At Titan unlike Mars, a lower dielectric contrast is expected between the atmosphere and the medium that will significantly help the subsurface investigation where a higher SNR is required.

At Enceladus, observations as a function of latitude will be important in order to probe lateral variations in temperature and composition, which are suggested by large variations in surface morphology. Temperatures are expected to be colder closer the north pole, as indicated by cratering record (Porco et al. 2006), where the radar signal may penetrate as deep as 50 km.

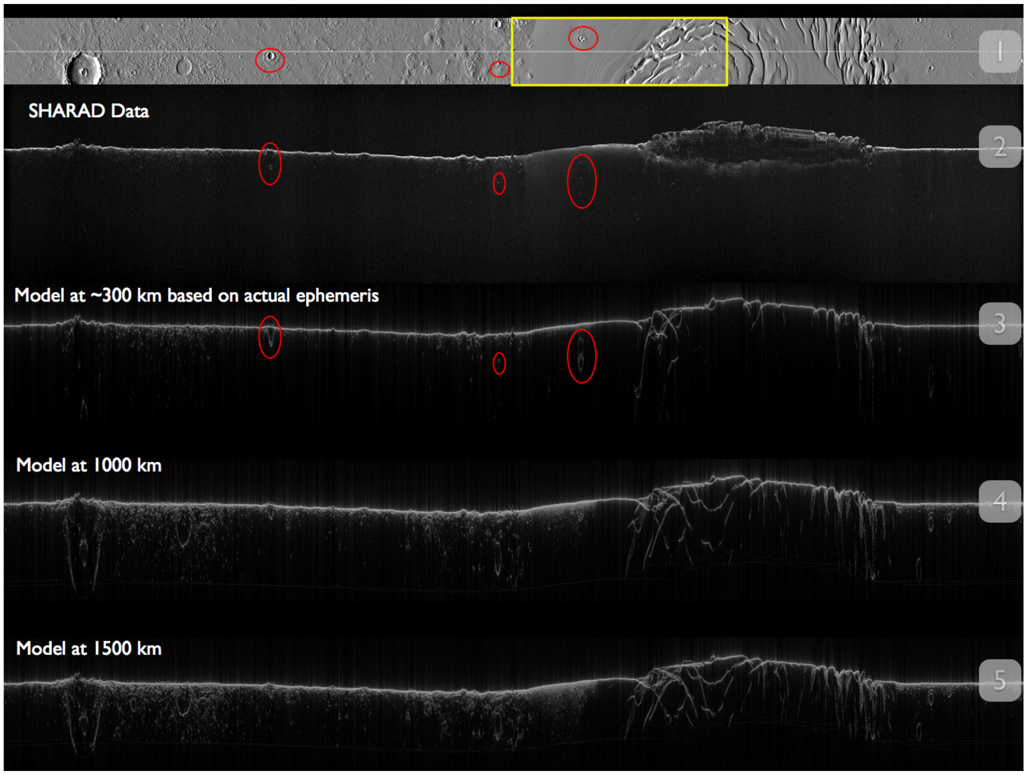


Figure 2.4-8. *Comparing expected performance of TiPRA to SHARAD: 1) SHARAD ground track topography based on MOLA data, 200 km wide and 3682 km long, 2) SHARAD radargram over the Mars northern plain, 3) Modeled radargram using actual Mars Reconnaissance Orbiter spacecraft ephemeris (altitude of ~300 km) and MOLA topography, 4) Same model as 3 with altitude changed to 1000 km showing a noticeable change in the coherent clutter signature with a observable increase in overall clutter, 5) with altitude changed to 1500 km (TiPRA nominal operating altitude) showing minor changes from 1000 km. The red ovals point three instances of cross-track clutter with coherent signature in the radargram.*

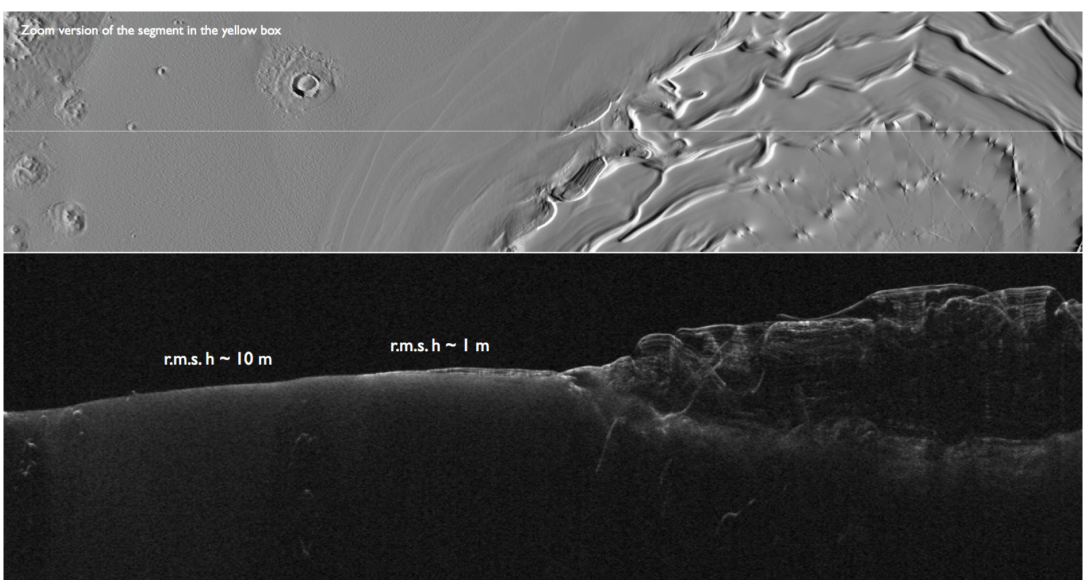


Figure 2.4-9. *Detailed version of segment inside the yellow box in* ***Figure 2.4-8****. There is noticeable coherent echo strength change between areas with different roughness level.*

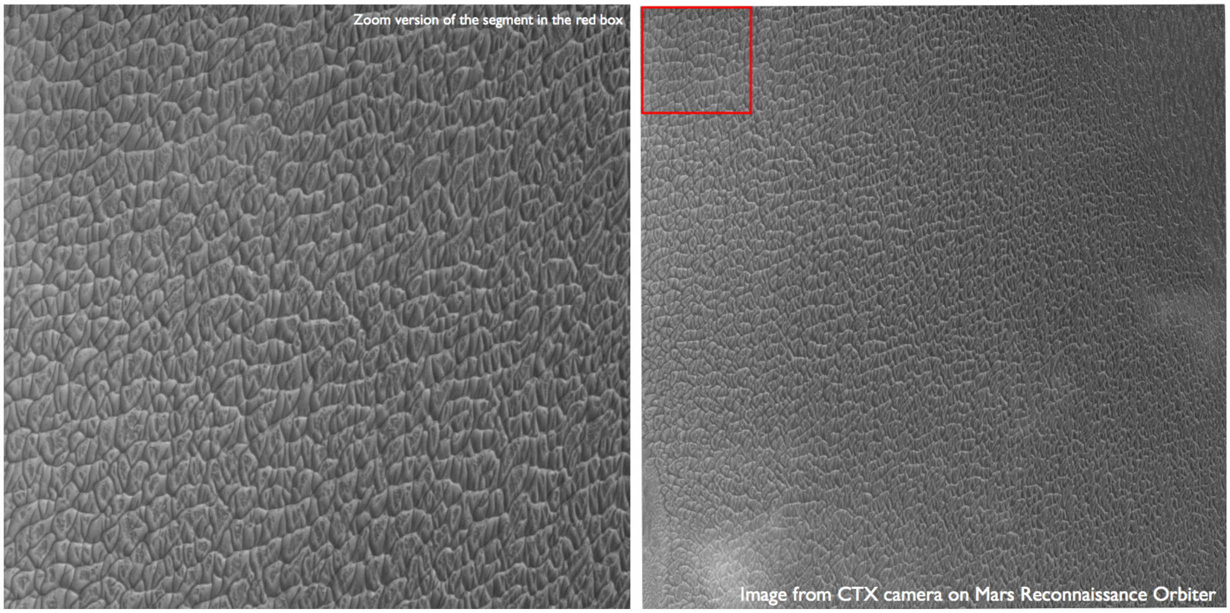


Figure 2.4-10. *High resolution CTX image of the sand dunes with ~10 m rms height within a 5 km box.*

2.4.3.3 Polymer Mass Spectrometer (PMS)

Determining the identification and abundance of all species in the atmosphere is vital for understanding the processes occurring within the atmosphere and on Titan's surface and are key measurement requirements. The approach to accomplishing this requirement is *in situ* mass spectrometry. The results of the Cassini mission have demonstrated a level of organic complexity in Titan's upper atmosphere well above anticipation. The existence of complex hydrocarbons and nitriles in the form of neutrals, positive ions, and negative ions is strongly suggested by the data. However, a definitive determination and understanding of the chemistry awaits the improved mass range and mass resolution provided by the measurement of neutrals, positive ions, and negative ions by the PMS instrument onboard the TSSM orbiter. PMS would have the mass resolution to separate hydrocarbons from nitriles and to understand the variation of the stable isotopes of H, C, and N that form these complex molecules. This knowledge is crucial in understanding the organic chemical factory at Titan and how it might be similar or different from chemical processes in the interstellar medium.

The Polymer Mass Spectrometer will have: 1) dynamic range ($>10^8$), 2) mass range (10,000 Da), and 3) mass resolution ($M/\Delta M$ ~10,000 at 1% of peak height). The origin of each of these instrument specifications is discussed below.

The requirement for dynamic range is set by the demands on covering the altitude range and associated density range from the exobase at 1450 km (pressure = 1.9×10^{-12} bar) to altitudes below the peak of Lyman alpha absorption by methane, which occurs at 700 km (pressure = 2.8×10^{-8} bar). Furthermore, it is critical to be able to measure both primary atmospheric constituents and minor species with mixing ratios of at least 10^{-4} at the exobase. Reaching saturation on molecular nitrogen at the lowest altitudes is acceptable, but its dissociative ionization fragment at mass 14 must be capable of being measured (~1 part in 20 of the main peak at mass 28). Therefore, the requirement is eight orders of magnitude.

The mass range is simply set by the observations of Cassini—both CAPS and UVIS see monomers that exceed 10,000 Da and thus it is required that PMS can measure these particles as both neutrals and negative ions (Waite et al. 2007).

The mass resolution is again derived from Cassini observations. The origin is two fold: 1) resolution of C, N, and H isotope ratios in compounds up to at least 150, 150, and 50 Da,

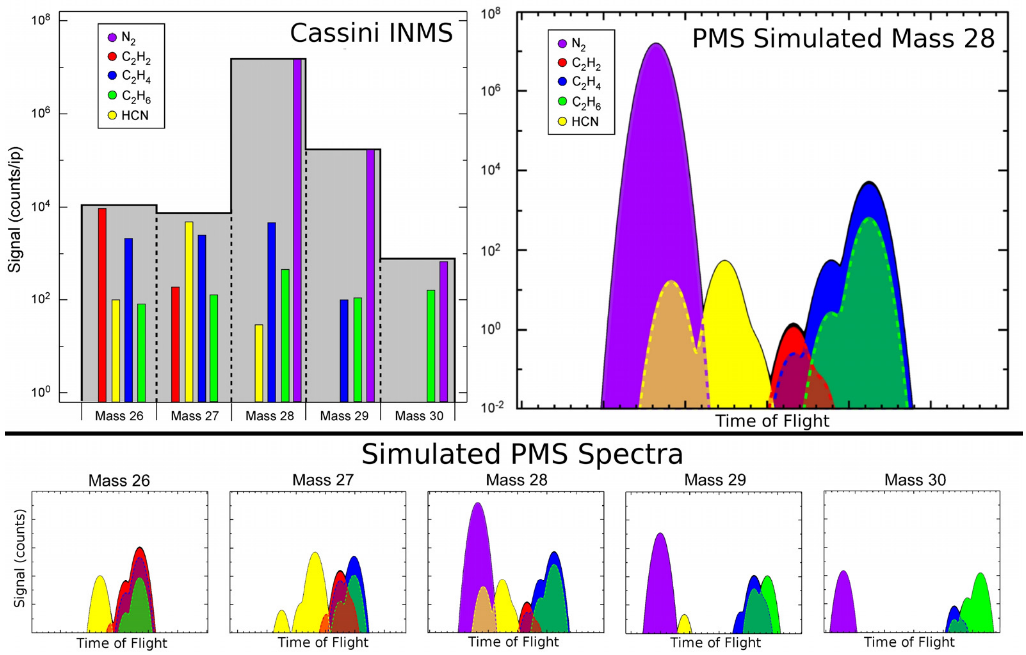


Figure 2.4-11. The upper left panel shows Cassini INMS data (in grey) taken at an altitude of 950 km. The colored bars indicate each individual compound's contribution to the mass channel as determined by a deconvolution using INMS calibration data. The upper right and bottom panels show simulated PMS spectra. Each time of flight mass spectra has an x-axis range of 300 ns. This demonstrates how high-resolution mass spectrometry produces unambiguous results through separation. Shown is the separation of C_2 group hydrocarbons from hydrogen cyanide (HCN).

respectively, and 2) distinguishing nitrile and hydrocarbon species at masses up to 130 Da.

Both GCMS and INMS have measured the nitrogen isotopic ratios in molecular nitrogen and find that they are a factor of two in favor of the lighter isotope (Mandt et al. 2008) as compared to the hydrogen cyanide measured by the CIRS in the stratosphere (Marten et al. 2002, Gurwell 2004). Furthermore, CIRS measures carbon isotopes in C_2 hydrocarbons that are isotopically heavier than methane (Nixon et al. 2008b). Finally, INMS finds a dramatically heavier D/H ratio in the upper atmosphere than the surface value from GCMS. The C, N, and H isotopic ratios are used to infer atmospheric evolution, both escape and climate change. Furthermore, the carbon isotopic ratios can be used to infer metabolic processes if determined accurately enough. Therefore, it is extremely important that PMS measures these ratios over the altitude range from 700 to 1500 km with an accuracy of better than 1%. This requires a minimum mass resolution of 6000 at 1% of peak amplitude to separate the isotopologues from 1 to 150 Da for carbon and nitrogen and 50 for hydrogen isotopologues, which are inferred from the Cassini data.

The presence of nitrogen modifies the hydrocarbon chemistry and introduces important nitrile chemistry in the upper atmosphere of Titan (Imanaka et al. 2004, Vuitton et al. 2008). Furthermore, this important chemistry extends to masses that exceed 300 Da and appear to play a major role in negative ion formation due to the high electron affinity of nitrile terminal groups attached to large aromatic compounds. Thus, the requirement for PMS is that it must resolve nitriles from near equivalent mass hydrocarbon compounds at masses up to 130 Da. This requires a mass resolution at 1% of peak height of 10,000. A very important example of this is being able to measure hydrogen cyanide (the major atmospheric coolant and father of all nitrile compounds) in the presence of molecular nitrogen, ethylene, acetylene, and ethane, which is illustrated in **Figure 2.4-11**.

2.4.3.4 Sub-Millimeter Spectrometer (SMS)

The measurement requirements for this type of instrument are to determine the chemistry and dynamics in the poorly understood region from 400–900 km. Submillimeter heterodyne techniques have proven useful for measuring atmospheric trace constituent abundances and physical properties under all climate conditions, including high dust loading. The strong sub-millimeter transitions of polar molecules permit detections of numerous trace species at parts per trillion to parts per billion sensitivity. As an emission measurement, observations are carried out in a passive mode and can be done on a continuous basis. At these wavelengths, a moderate-sized telescope (~15 cm) can yield high- spatial resolution measurements, while ultrahigh spectral resolution (nu/delta nu = 5×10^6) provides clear line separation and well-defined line profiles allowing retrievals of the species vertical distributions and direct measurement of winds.

The Sub-Millimeter Spectrometer (SMS) instrument is a highly sensitive heterodyne receiver with ~100 GHz of bandwidth. Uncooled Schottky diode detectors are used to achieve high sensitivity along with large operational bandwidth. The instrument is designed to meet specific science objectives of the mission. The measurement of abundances of trace gases and isotopologues along with temperature profiles in Titan's atmosphere from 400–900 km are made possible by having a wideband receiver with the capability of measuring brightness temperatures with 1 K accuracy.

The important instrument specifications for SMS are 1) the spectral range, 2) the spectral resolution 3), the vertical and spatial coverage and resolution of the measurements, and 4) the sensitivity and time resolution.

The spectral range for SMS (i.e., the choice of observing bands) is dictated by 1) the need to observe strong lines of CO and HCN (and possibly CH_4) to derive the thermal field up to altitudes of at least 1200 km, 2) the need to observe lines with a variety of strengths to constrain the wind field as a function of altitude from <200 to >1200 km, and 3) the need to observe a rich suite of molecular species to constrain the chemistry of Titan's stratosphere, mesosphere and thermosphere. In addition to the above molecules, the chosen spectral region, 540–660 GHz, includes lines due to HC_3N, CH_3CN, CH_3CCH, NH_3, CH_2NH, HDO and DCN.

The spectral resolution (300 kHz) is driven by wind measurements. At 600 GHz, this corresponds to a channel resolution of 150 m/s, and the high SNR (of order 30–100 per channel for 1 minute integration) will permit measuring winds with an absolute accuracy of 3–4 m/s. This is appropriate, as zonal winds of 60–150 m/s have been measured by this technique (Moreno et al. 2005), while meridional winds are expected to be typically an order of magnitude less.

SMS is able to make measurements over at least the 200–1200 km range, making it well suited, in particular, to the study of the poorly explored region from 400–900 km. Detailed atmospheric studies, including detection of wave-like structures such as those seen in temperature, haze, and composition by a variety of techniques (e.g., Fulchignoni et al. 2005, Porco et al. 2005, Teanby et al. 2006), require a sub-scale height resolution, which will be achieved by a ~15 cm mirror, providing e.g., ~8 km resolution from a 2000 km distance. Obtaining global (i.e., 3-D) fields of temperature, winds and composition will be best achieved with a primarily limb viewing observing mode, maximizing vertical resolution and vertical coverage. Limb scanning will be facilitated by employing a one-dimension articulation mechanism. Both in-track and off-track views are needed. The former is required to measure meridional winds and to be able to reach polar latitudes in limb view, while the latter is needed to measure zonal winds. The observation of poles in limb geometry is particularly needed in the context of a global atmospheric study as these regions appear to be vortices of peculiar (i.e., enhanced) composition and dynamics.

The required precision on the SMS signals (brightness temperatures) is typically 1 K. In most of the atmosphere, this directly translates into a 1 K precision on the measured atmospheric temperature, which is adequate for dynamical studies (e.g., computing the zonal wind from the thermal field and comparing it with the direct measurements). This implies typical individual integration times on the

Table 2.4-3. *Flowdown of mission science requirements and how they are implemented on SMS.*

Science Objectives	Technique/driver	Instrumentation	Implementation	Verifiable Metric
Abundances of trace gas and isotopologues (H_2O, CO, HCN, HC_3N, CH_3CN, CH_3CCH, NH_3, CH_2HN, and CH_4).	Very high resolution sub-mm heterodyne spectroscopy	Tunable submillimeter high spectral resolution spectrometer Uncooled state of the art detector	540-640 GHz tunable receiver to observe specific molecules and transitions Resolution 2x106 or better	Receiver Noise Temp ~8000 K single side band (ΔT~1 K with 1 min integration & 1 MHz BW)
Vertical scale height resolution or better	Telescope sized for specified orbit	Telescope size set by footprint at limb for 1500 km orbit and 2000 km	Telescope diameter to provide <10 km altitude resolution	Telescope dia = 15 cm (parabolic reflector) FOV~0.91 deg (FOV defined as 4*HPBW)
Winds in 5–10 m/s range	Heterodyne spectroscopy with USO	Need ultra stable oscillator (USO)	USO to provide frequency stability to measure winds	Δf/f >1010 (freq stability)
Temperature	Measure line widths and multiple spectral lines	Same as abundances	High resolution backend spectrometer; USO	300 kHz resolution on spectrometer; >1010 (freq stability from USO)

order of 1 minute. While longer integration times would lead to increased precision, the need for relatively short integrations is dictated by the requirement of maintaining sufficient latitude and vertical resolution (for a 5 hr period orbit, the spacecraft moves by 1.25° in 1 minute).

The measurement of zonal and meridional winds is accomplished by articulating the primary, using a high resolution spectrometer and an ultra stable oscillator (USO). To measure the winds with an absolute precision of 3–4 m/s requires a spectrometer with 300 kHz resolution. Detailed atmospheric mapping of temperature, winds and molecular composition requires sub scale height vertical resolution. This is accomplished on SMS by sizing the primary reflector to provide ~8 km resolution from a 2000 km distance. At 600 GHz the reflector size is approximately 15 cm to accomplish this goal.

A summary of the mission science requirements and how they are implemented on SMS are shown in **Table 2.4-3**.

2.4.3.5 Thermal Infrared Spectrometer (TIRS)

The lower atmosphere, the troposphere and stratosphere, from the surface to 400 km will be investigated using a thermal infrared spectrometer. Thermal infrared spectrometers have been flown on several missions. Mid- and far-infrared spectroscopy have been used for decades to better understand the dynamics, thermal structure, and composition of planetary atmospheres, as well as surface temperatures of solid bodies. Fourier Transform spectrometers, such Voyager IRIS, and Cassini CIRS have been used to achieve high spectral resolution over a wide wavelength range. More recent advances have allowed for an expanded spectral range with multiple focal planes and variable spectral resolution to allow the trade between integration time and resolution. Current technologies allow for even better sensitivities and higher spectral resolution (0.1 cm^{-1}), sufficient for separating the emission lines of isotopologues of the hydrocarbons in Titan's atmosphere, such as those of HC_3N. **Figure 2.4-12** shows a region with 3 isotopes of HC_3N. and how an improvement in spectral resolution can achieve this separation, In addition to atmospheric composition, the proposed instrument can be used to determine Titan's atmospheric thermal structure and infer thermal winds.

As shown in **Figure 2.4-13**, Cassini CIRS can resolve (c) from (a) and (b), but not (a) from (b), at 0.5 cm^{-1} resolution. The apparent detection of the 663.1 peak, which is actually blended into the 663.3 peak, is bogus: the model is correctly predicting it because it can retrieve the $^{12}C/^{13}C$ from the isolated 658.7 cm^{-1} line. i.e., the retrieval model shown is calculating at 0.25 cm^{-1} grid but with 0.5 cm^{-1} line width FWHM so it appears that CIRS can separate 663.3 from 663.1 when, in fact, it cannot. Note that the 663.1 feature appears twice as strong as the 658.7 feature in the model, because there are two isotopes with emissions there instead of one.

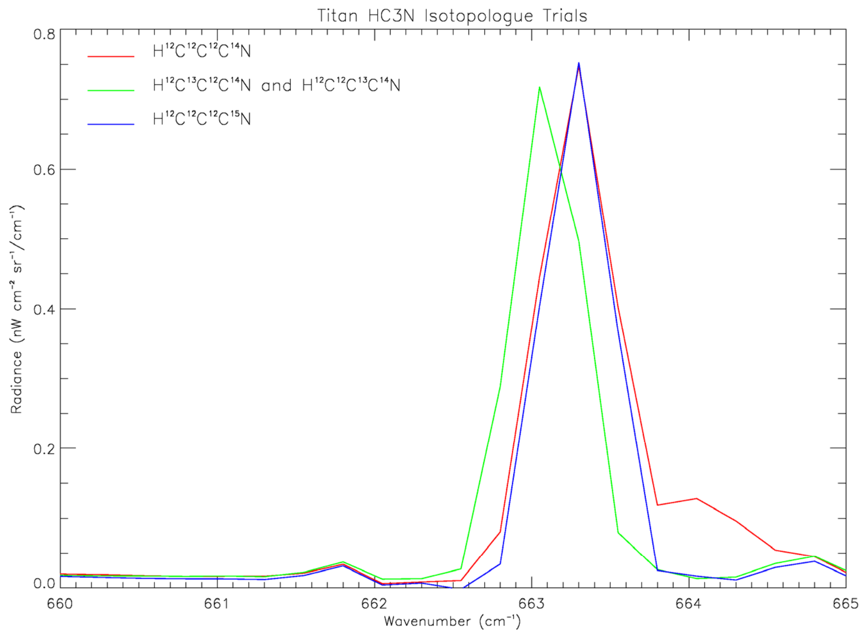


Figure 2.4-12. *A region with 3 isotopes of HC_3N. At 0.1 cm^{-1} spectral resolution, the three peaks can be resolved, whereas, at 0.5 cm^{-1}, they cannot.*

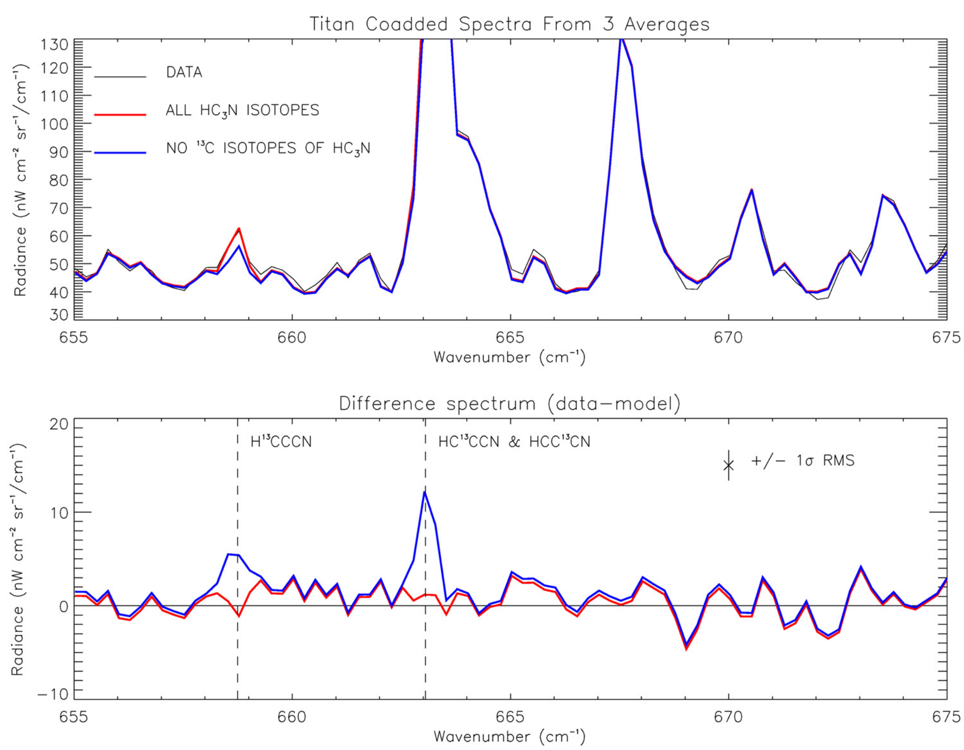


Figure 2.4-13. *a) At 663.3 is the main HC_3N plus the ^{15}N isotopologue (i.e., molecular isotope), b) At 663.1 are the two carbon isotopes not involved in the HC bending mode, c) At 658.7 is the $H(^{13}C)CCN$ isotope involved in the HC bending mode.*

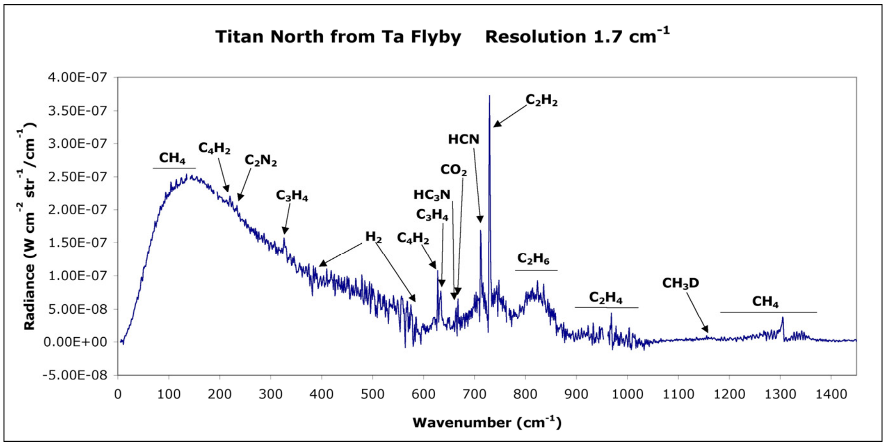


Figure 2.4-14. *A Titan spectrum as seen by Cassini/CIRS at a resolution of 1.7 cm^{-1}. TIRS will achieve 10 times higher resolution and allow for the detection of more complex species and a more precise determination of their spatial distributions.*

TIRS is required to have: 1) a spectral range from 7 to 333 µm or beyond, 2) spectral resolutions from 0.1 to 15 cm^{-1}, and 3) sensitivity equivalent to Cassini CIRS or better.

TIRS is based on the heritage from Voyager IRIS and Cassini CIRS. It improves on the wavelength coverage with respect to IRIS, and on the sensitivity and spectral resolution of both previous instruments. The need for these improvements is outlined below.

As Infrared Space Observatory (ISO) measurements first demonstrated in 1997, high spectral resolution (0.5 cm^{-1} or higher) gives access to the detection and vertical characterization of several gaseous components in Titan's atmosphere. It was ISO which first allowed the detection of water vapor (Coustenis et al. 1998), the separation of contributions of different molecules as well as the detection of benzene on Titan (Coustenis et al. 2003).

CIRS confirmed these detections (Flasar et al. 2005) and further produced evidence for several new isotopic species in C_2 hydrocarbons and nitriles (Vinatier et al. 2007a; Nixon et al. 2008a, b; Jennings et al. 2008; Coustenis et al. 2007), measured the D/H ratio with higher precision (Coustenis et al. 2007; Bézard et al. 2007) and gave access through limb-viewing to gaseous vertical distributions (Vinatier et al. 2007b; Teanby et al. 2007). In addition, the abundances and latitudinal variations of the species in the stratosphere were determined (Teanby et al. 2006, 2008; Coustenis et al. 2007; de Kok et al. 2007a; Nixon et al. 2007) and information on the aerosols was derived (de Kok et al. 2007b). However, further measurements are needed from Titan orbit and at different times in Titan's year in order to fully study temporal changes in temperature structure, such as the tilted polar temperatures first observed by CIRS (Achterberg et al. 2008). In addition, isotopic abundances, composition in the troposphere and stratosphere, and detailed vertical and horizontal temperature structure require an instrument beyond the capability of CIRS (**Figure 2.4-14**).

The wavelength range (7–333 µm or 30–1400 cm^{-1}) and spectral resolution (0.1–0.5 cm^{-1}) of TIRS is driven by the need to measure temperatures and atmospheric composition with higher precision than previously attained. For example, there are many atmospheric constituents with emission/absorption lines in the wavelength range of 30 to 1400 cm^{-1}, including HCN from 30–720 cm^{-1}, H_2O from 80 to 160 cm^{-1}, CO from 25 to 75 cm^{-1}, C_2H_2 at 728 cm^{-1}, CO_2 at 667 cm^{-1} and C_2H_6 from 800 out to 1400 cm^{-1}. Other chemically significant heavier hydrocarbons and nitriles but with weaker bands, such as C_3H_4, C_4H_2, C_6H_6, HC_3N, have spectral signatures in the TIRS range. The study of the abundances of all these chemical compounds and of their isotopologues, requires high spectral resolution, not only to be able to separate the various contributions but also to infer vertical distributions by resolving the stronger bands (C_2H_2, C_2H_6 and HCN for instance).

The latitudinal variations obtained by TIRS will be complementary to the previous Voy-

ager, ISO and Cassini observations, providing a better understanding of the seasonal phenomena on Titan. In addition, new, more complex molecules will be detected with TIRS, as with Cassini/CIRS and ISO/SWS in the past. The ultimate purpose of these composition studies with TIRS is to infer the highest degree of complexity attained by the organic chemistry in Titan's stratosphere and to provide the link with the upper atmosphere's recent heavy ion detections. In addition, studies of atmospheric aerosols and condensates also require far-IR wavelengths, as their signatures can be seen against the background continuum and nearby gases at these wavelengths. The sub-mm range (10–600 cm^{-1}) of TIRS will give access with better sensitivity than CIRS to the rotational lines of a number of important molecules in Titan's atmosphere (like CH_4, CO, and HCN, as well as their isotopes). Furthermore, the haze properties and condensates can be better defined from this region with TIRS (Samuelson et al. 2007).

Temperature studies of Titan are performed using the relative strengths of nitrogen pressure-induced absorptions from 15 to 90 cm^{-1}, and through the relative strengths of collision-induced and rotational absorption/emission lines of methane from 1290 to 1320 cm^{-1} and 60 to 140 cm^{-1}, respectively. These do not require the high spectral resolution needed for composition, and spectral resolutions in the range 3 to 15 cm^{-1} will suffice in most cases (Achterberg et al. 2008). It is desirable to have an instrument that can produce spectra with varying spectral resolution, because the lower spectra resolution data do not require as long a scan time (in an interferometer) to produce. Thus, spatial resolution can be preserved and more spectra can be obtained in a given observational period. In select cases, even lower spectral resolution could be desirable, such as for temperature sounding along narrow polar vents on Enceladus during a fast flyby. With variable scan length options, this is not a problem.

As envisaged, the SNR of TIRS would be comparable to CIRS (Flasar et al. 2004). The basis for this assertion is as follows. For the Far IR, TIRS will have better detectors. CIRS has thermoelectric detectors fabricated at Karlsruhe University, Karlsruhe, Germany (Birkholz 1987) with the highest optical detectivity of about 4×10^9 cm $Hz^{1/2}$ W^{-1}, for a few Hz and short wavelengths. By comparison, TIRS will use high Tc superconductor bolometers, with the same absorber (gold black). Lakew et al (Lakew 2000) show a peak optical detectivity of 1.2×10^9 cm $Hz^{1/2}$ W^{-1} with the superconductor material yttrium barium copper oxide (YBCO). The best Brasunas et al. (2008) achieved was 2.0×10^{10} cm $Hz^{1/2}$ W^{-1} with gadolinium barium copper oxide (GBCO). So, five times better detectivity is achievable, with a comparable time constant (50 to 100 ms). Because TIRS has a lower mass/volume/power than CIRS, the optical collecting area is smaller and thus the SNR is reduced. CIRS has 50 cm optics, so even with a smaller primary mirror, there is a slight improvement in SNR.

The story for the mid-IR is different. Here the detectors are comparable, since CIRS and TIRS would both employ photovoltaic and photoconductive HgCdTe. Improvement in S/N here comes from opening up the field of view (this is not done in the FIR, as the CIRS FIR FOV is already quite large). TIRS can have a larger FOV compared with CIRS due to the relative geometries (orbiter vs. flyby). The MIR FOV is increased five-fold, so with 15 cm optics (versus 50 cm) there is 1.5*1.5 greater etendue (area – solid angle product), or about a 2-fold increase in SNR.

2.4.3.6 Magnetometer and Plasma Package (MAPP)

There are numerous requirements for measuring the magnetic field and determining the properties of, and energy input from thermal-magnetospheric sources, such as electrons and ions. The JSDT felt that the best way to obtain coordinated results for the space physics package was to have a coordinated science team and instrument package. Some mass and power savings results from the instrument synergy, but the real science enhancements and cost savings comes from a coordinated science team (see §4.2.2.6 for details). Consequently, MAPP comprises a Magnetometer and a Plasma Instrument composed of a Langmuir probe, Plasma spectrometer and an Energetic Particle Spectrometer.

Magnetometer

The measurement requirements of a magnetometer instrument onboard the TSSM orbiter

include resolution of any Titan intrinsic magnetic field; measurement of induced subsurface signatures to confirm subsurface liquid as well as place constraints on the conductivity and depth of any ocean; characterize the magnetic history of the crust and support plasma and energetic particle measurements. Observations from a Titan orbiter made over a period of months will allow the varying multiple frequencies in the signal to be resolved which is critical in defining both the background inducing magnetic field as well as the resulting induction signature; and then enable possible resolution of any remaining intrinsic magnetic field. In order to unequivocally constrain the induction signatures these orbiter observations will be made in conjunction with magnetic field observations on the montgolfière.

An instrument that can accomplish those goals incorporates fluxgate magnetometer sensors, which have a long and well established heritage in the measurement of planetary fields throughout the solar system on missions such as Voyager, Galileo, Cassini, Cluster and Venus Express. The sensing technology is mature and well developed. Tri-axial sensors permit the detection of the magnetic field vector and can operate with good sensitivity in the range 0–64 Hz. The sensor technology has evolved to a state where noise and offset stability are primarily limited to the fundamental material properties of the permeable core. Noise levels of the order 11 pTrms and temperature offset coefficients of better than 0.1nT/^{o}C have been attained.

Small field variations are routinely measured in the solar wind by the Cluster fluxgate magnetometers with 8 pT resolution and accuracies of better than 0.1 nT. In these regions, where the ambient field is less than 10 nT, phenomena such as inter-planetary shocks, turbulent cascades and field rotations are studied using magnetometer data. Selene includes a fluxgate magnetometer with accuracy better than 0.1 nT. It has measured lunar field perturbations related to lunar surface activity at 100 km altitude based on a 1–2 nT variation seen at the sensor. The measuring resolution of the instruments will enable perturbations of order 0.02–0.04 nT in a background magnetic field of ~100 nT to be made.

An orbiter magnetometer is a necessary instrument in order to resolve external versus internal magnetic field signatures at Titan as well as enabling a study of Saturn's magnetosphere and the plasma interaction with Titan. To gain an understanding of the interior structure of Titan (and possibly that of Enceladus via flybys) magnetic field observations are required from the Titan orbiter to enable a resolution to be made between induced or intrinsic magnetic field signatures. Such observations will allow resolution of the depth of any liquid oceans which may be beneath their icy surfaces, the strength of any induced magnetic fields arising within these oceans, and the conductivity of the liquid.

Driving requirements for the magnetometer include the need to have measurements made over periods of months in order to resolve multiple frequencies. For example to resolve the effects of a single frequency (that of the rotation period ~ 10 hrs) one would need 10 hr × 20 rotation periods so ~10 days. In order to study frequencies linked to Titan’s orbital period of 16 days— one would require ~10–20 orbital periods and so from 4–10 months.

The magnetic induction effect at Titan is due to the periodic occurrences of breakthroughs of the total outer magnetospheric field through into Titan's ionosphere. These are expected to occur in broad recurring intervals around local times of 06.00 Saturn Local Time (SLT) in Titan's orbit. The basic physics of the mechanisms of frozen-in and diffusing magnetic fields have been studied on a multitude of Cassini flybys and is reasonably well understood. However, without observations on an orbiter the inducing magnetic signal is not known and the balloon/surface magnetometers will be blind to the field which is causing any induced signatures. In order to use the induction technique one must always be able to separate the inducing from the induced fields. In addition, in order to be able to resolve any remaining small dynamo magnetic field one must be able to distinguish it from the external magnetic fields breaking through the ionosphere. In order to define both the inducing magnetic field at Titan and the resulting induction signal (which arises in response to a time-variable inducing field), simultaneous measurements from a Titan orbiter, and/or a balloon-borne platform / lander are desirable. Multi-frequency sounding at frequencies which enable probing of the interior is neces-

sary in order to constrain the location and thickness of any subsurface ocean. Titan is immersed in a time variable inducing magnetic field at all times. The two main sources of this time varying signal are local time changes as Titan orbits around Saturn every 16 days, of order 2–4 nT, and the 10 hr 45 minute period from the tilted current sheet of Saturn with a similar amplitude of 2–4 nT. The two principal frequencies thus available for the probing are those due to Saturn's rotation and to Titan's orbital period. The time variable inducing magnetic field in the vicinity of Titan is always less than 100 nT (average background field) and therefore the instrument will measure perturbations of order a few nT on top of that (ideally with a resolution of order 0.02–0.04 nT). Such resolution is easily obtainable with a fluxgate magnetometer on the Titan orbiter.

The requirement of a magnetometer instrument is to continuously measure the magnetic field magnitude and direction to at least 1 s time resolution during the mission. Magnetometers flown on recent outer planetary missions such as Galileo and Cassini have revealed the capability of these instruments to resolve intrinsic versus induced signatures at Europa as well as resolve the presence of an atmosphere at Enceladus, both discoveries required measurement of fractions of nT perturbations in a background field of hundreds of nT. The Cassini spacecraft will not allow resolution of the internal structure of Titan although it has made, and will continue to make, numerous flybys of Titan because it requires measurements over periods of months (via an orbiting spacecraft) in order to carry out the multi-frequency sounding at frequencies which allow probing of the interior. Thus the proven stability of the fluxgate sensors is vitally important (see **Figure 2.4-15**).

With a single sensor it is impossible to separate the offset due to any interference field from the spacecraft from the offset from the sensor itself, so the offset data presented is the sum of the offset from the sensor and the offset due to any contamination field generated by the spacecraft. For Cassini the spacecraft contamination field is low due to the long boom length (12 m) and the consequent large separation of the sensor and the interference field. However, there can be seen a slight

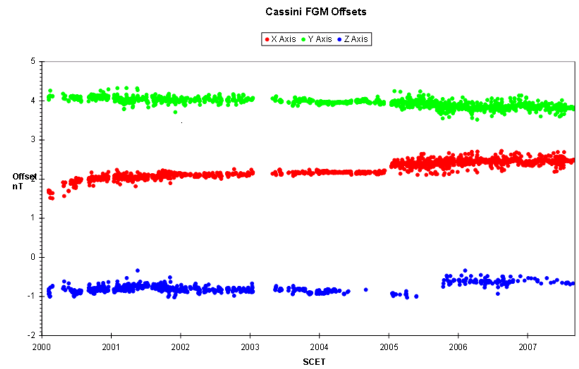


Figure 2.4-15. *The stability of the fluxgate sensor over time is well demonstrated by over seven years of data from the Cassini fluxgate sensor.*

effect (step change up to ~0.2 nT) in the offsets due to the release of the Huygens probe at the end of 2004. In addition, the offset determination after 2004 becomes more scattered. This is an indication of the difficulty of accurately determining the offset in a relatively disturbed field around Saturn rather than any variation in the sensor offset itself. Before the end of 2004, the offset was determined using statistical methods which can be used in the quiet solar wind during cruise. Following the end of 2004 when the spacecraft entered the relatively disturbed field around Saturn statistical determination of offsets was no longer possible, and offsets have been calculated using spacecraft rolls. The conclusion from the Cassini fluxgate experience, therefore, is that the offsets of this sensor design are inherently very stable.

Magnetometer measurements have played a crucial role over the years across many missions. For example, some of the most high profile discoveries include detection of the atmosphere at Enceladus, crustal fields on Mars and discovery of the longest comet tail found to date. It is expected that similar discoveries will be made at Titan.

Plasma Instrument

The main measurement requirements are determining the deposition of radiation into Titan's atmosphere, quantifying the sources of chemical energy for atmospheric chemistry and determining the atmospheric evolution of Titan.

The plasma instrument will consist of ion and electron detectors covering a range of energies from ~0.1 eV to 1 MeV. The wide range of energies to be measured necessitates different techniques to measure the ions and electrons— namely a Langmuir probe to cover thermal populations in high density regions (e.g., Titan's ionosphere) and to assess spacecraft potential, particularly when this is negative in high density regions; a plasma spectrometer capable of measuring electrons and ions in the range 1 eV–30 keV, with mass discrimination, covering the peak of the magnetospheric electron and ion populations; and an energetic particle instrument capable of measuring ions and electrons from 10 keV–1 MeV and covering important populations in Saturn's magnetosphere. The required field of view is ideally 4 pi, but 2 pi including the ram direction and nominal co-rotation direction is acceptable.

Langmuir Probe

The Langmuir probe is ideally suited to measuring the thermal plasma in and near Titan's ionosphere. The density range of the probe covers the peak ionospheric density and lower densities in the Titan-ionospheric interaction region and also determines the electron temperatures relevant to the ionosphere. The Langmuir probe can also contribute to characterizing ions, given modeled or measured composition.

The requirement for the Langmuir probe is to measure thermal plasmas in Titan's ionosphere over a range of densities from 10 to 10^6 cm^{-3} and temperatures from 0.01 to 10 eV. This range covers that expected for Titan's ionosphere based on Cassini measurements and is necessary to map the thermal plasma in Titan's ionosphere from the orbiter.

The proposed Langmuir probe would have strong heritage to the Cassini Langmuir probe which has proven its effectiveness in over 40 flybys of Titan. While Cassini has provided more than 40 flybys of Titan in its prime mission, these flybys occurred over a time scale of 4 years with very brief (of the order of an hour) roughly once per month. Most of the flybys sample a highly localized latitude and longitude range with Titan at various Saturn local times. Hence, it is very difficult to differentiate between temporal, latitudinal, solar illumination, Saturn plasma interaction, and other effects. A high inclination orbiter repeatedly samples a wide range of latitudes on short time scales (compared to Titan's orbital period) and over the course of a Titan orbit, samples varying solar illumination versus magnetospheric plasma flow directions. Hence, the Langmuir probe on the orbiter builds up a much more regular and systematic sample of the electron density and temperature over the course of a Titan orbit. Further, the integrated time in and near Titan's ionosphere during a Titan orbit is more than an order of magnitude more time than accumulated by Cassini over the entire 4-year prime mission. Hence, repeating the Langmuir probe observations a few months or a year later provides an opportunity to unravel the temporal variations in a systematic manner. **Figure 2.4-16** shows the measurements made during the T_B flyby of Titan.

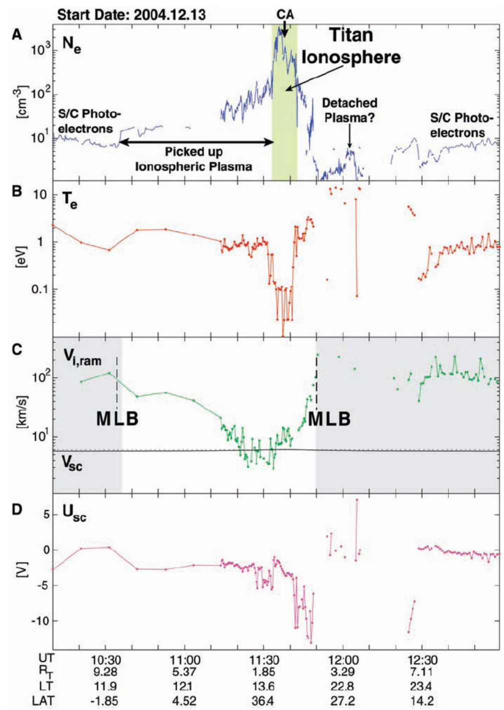


Figure 2.4-16. *Langmuir probe measurements made during the TB flyby of Titan. In the top panel (A) the electron density is plotted, with densities ranging from just over 1 cm^{-3} to a few thousand cm^{-3}. In panel B, electron temperatures are measured in the range of 0.02 to 10 eV. Panel C shows the ion ram speed is shown. In panel D, the spacecraft potential is given (Wahlund 2005).*

Plasma Spectrometer

The plasma spectrometer will determine the principal populations in Saturn's magnetosphere, which have important interactions with Titan's atmosphere. In addition, the energy and angular spectrum of the ionospheric population, and of escaping plasma, is measured.

Plasma instruments have flown successfully for more than 40 years. There are several different technologies and the performance requirements for the Titan orbiter. This study uses the PEPE instrument (Young et. al. 2007), which is similar to CAPS and flew on Deep Space 1, as the plasma instrument for the planning payload. It also has the essential quality of producing various ion fragments in the time of flight mass spectrum which will allow one to separate carbon, nitrogen and oxygen based incident atomic and molecular ions (i.e., O^+ vs CH_4^+, OH^+ vs CH_5^+, N_2^+ vs CO^+ vs $HCNH^+$).

Electrons from the magnetosphere in the keV energy range are absorbed by Titan's atmosphere and this contributes to ionization and heating of the ionosphere, particularly on the night side. On the day side, solar radiation dominates, but magnetospheric electron input also plays a role. Also, impacting ions deposit particles (e.g., oxygen) and energy at lower altitudes, altering the energy and composition balance there. During the TSSM mission it will be vital to measure the input populations at the top of Titan's atmosphere while the surface elements are active, as well as during earlier flybys. The TSSM plasma instrumentation will have superior angular range to the Cassini instrumentation, permitting, for the first time, full determination of magnetospheric particles as energy sources.

Ion measurements give information on particles being lost by Titan, including pickup ions. Again, full angular coverage is vital to distinguish between ring and field aligned particle distributions. Mass resolution is required to be sufficient to resolve hydrogen, water group, methane group and ammonia group ions, to assess pickup and other mechanisms of ion escape. The energy resolution of the electron spectrometer will be good enough to cover ionospheric photoelectrons which may play a key role in the escape process. Ion and electron data with full angular coverage are vital to determine the escape processes, which in turn determine the atmospheric evolution of Titan.

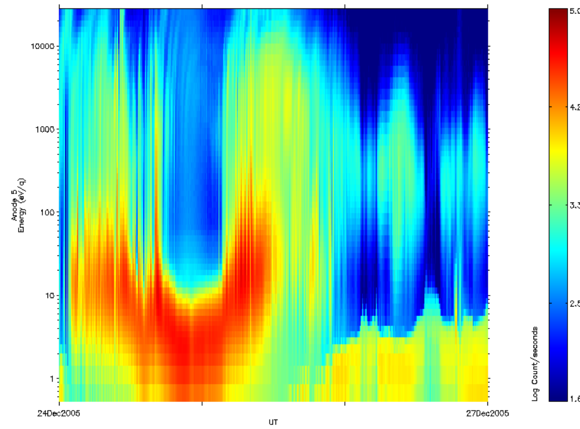


Figure 2.4-17. *Titan is immersed in Saturn's highly variable magnetosphere. An example of the variability near a Titan encounter is shown by the electron intensities seen by CAPS-ELS (Coates et al. 2007b). TSSM is required to measure full ion and electron fluxes during the montgolfière and lander missions.*

In Titan's ionosphere, one of the key discoveries by Cassini-Huygens was the existence of unexpectedly heavy positive ions, and completely unexpected negative ions at ~950–1200 km (Waite et al. 2007, Coates et al. 2007). The chemistry at work in the atmosphere is therefore more complex than anticipated. These species, reaching at least 10,000 Da/charge, may fall through the atmosphere as aerosols and interact with the surface. It is vital therefore that the fields of view of the plasma instrument include the ram direction to assess these populations and to measure them during the mission of the TSSM surface elements (**Figure 2.4-17**).

A secondary set of objectives for the plasma instrument are related to Saturn's magnetosphere. These include the different roles played by reconnection, the origin of spin periodicities in the magnetosphere, magnetospheric plasma convection patterns, and much of the physics of rapidly rotating magnetodisks. While much progress has been made with Cassini, the full angular coverage obtained by TSSM will provide an enormous leap in our understanding of the plasma region.

Energetic Particle Spectrometer

The Energetic Particle Spectrometer is designed to measure the energetic particles that provide an important energy source to Titan and also characterize the nature of the magnetospheric environment in which Titan is embedded.

The driving requirements for the Energetic Particle Spectrometer is to measure ions in the energy range of 2 keV/nucleon to 5 MeV/nucleon and electrons in the range from 20 to 1000 keV. The energy range includes the ions that are the main energy input to Titan's atmosphere and ionosphere at altitudes between 500 and 1000 km. These ions can also contribute to most of the plasma pressure in the magnetosphere in the range from just outside the orbit of Enceladus to that of Titan. The energetic electrons measured by EPS are the most significant radiation source for the surface of Enceladus (see Sittler 2006).

From the data shown in **Figure 2.4-18**, the energy deposition as a function of altitude can be backed out. The pink contours in the top panel show the locus of the segmented field of view of the EPS, which would routinely provide information similar to this.

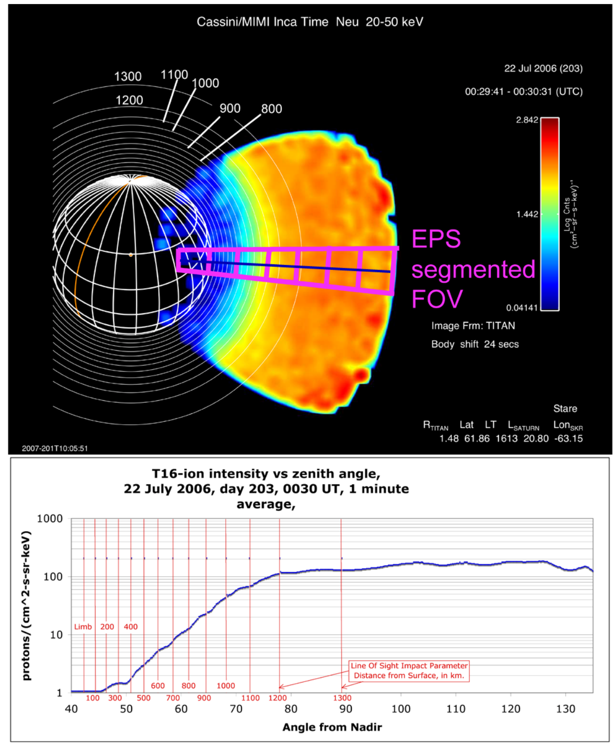


Figure 2.4-18. *Top, ion intensities within the Cassini/MIMI/INCA sensor, showing the absorption of ions as they traverse the atmosphere. White circles indicate the "impact parameter" closest approach altitude of an ion in its path to the sensor. The horizontal blue line indicates the locus of intensities shown in the Bottom panel, showing the ion intensity as a function of the depth of its penetration into the Titan atmosphere.*

2.4.3.7 Radio Science and Accelerometer (RSA)

Radio Science techniques have been utilized on practically every deep space mission and led to numerous discoveries. They are based on examining variations in the characteristics of the radio links between spacecraft and Earth to investigate the planetary interiors and atmospheres as well as various aspects of space physics and fundamental physics. Doppler tracking is a proven method for accurately investigating planetary gravitational fields. By moving to higher frequencies (less susceptible to interplanetary plasma noise) and using multiple links, calibrating the Earth tropospheric effects, and measuring or modeling and calibrating the effects on non-gravitational accelerations on the spacecraft, the quality of the RSA instrument data will lead to meeting the mission's scientific objectives. When mission geometries allow, atmospheric occultations will enable the investigation of temperature-pressure profiles and ionospheric densities.

Gravitational measurements will be inferred from measurements of the relative velocity between the spacecraft and ground stations, manifested as a Doppler shift in the radio link(s). One-way radio link will also yield temperature-pressure profiles for Titan's atmosphere via radio atmospheric occultations.

There are two driving requirements for the Radio Science and Accelerometer Instrument: The overall velocity measurement resolution is required to be 50 µm/s for a 60 s integration time, or the equivalent Allan deviation of the order of 10^{-14} (60 s) on the Ka-band link for the gravity measurements; and of the order of 10^{-13} (for 10 s integration time) for the occultation measurements (to meet the overall requirement, individual components of the instrument and system are required to perform better than the overall requirement, a tech-

nique which has been successfully demonstrated by Cassini).

The tracking accuracy is set by the objective to determine Titan's gravity field to degree seven for measurements performed at 1500 km altitude. This corresponds to a fractional measurement accuracy of 0.1 ppm of Titan's surface gravity field, which is about 1.3×10^{-5} cm/s^2. This level of accuracy requires using Ka-band for both uplink and downlink.

The Allan deviation or Doppler noise are equivalent measures of the noise affecting the signal. The strong requirement on the noise level will optimize the detection of lateral gravity anomalies with low spatial scales. As described in Asmar et al. (2005), there are two primary categories of noise sources: propagation (interplanetary plasma as well as Earth's ionosphere and troposphere) and non-gravitational forces due to, for example, atmospheric friction on the spacecraft, spacecraft thrusters, etc. Optimized correction of the dispersive media (interplanetary plasma and ionosphere) will be achieved using a dual-frequency transponder providing two-way coherent Doppler tracking: X-band and Ka-band, in both uplink and downlink modes. The troposphere is calibrated by independent measurements of the path delay via a water-vapor radiometer; this instrument is part of the Deep Space Network (used extensively and successfully for Cassini and other missions) and sits adjacent to the ground station and co-points with it to "see" the same air column. Non-gravitational forces can be estimated from the tri-axial accelerometer measurements whose noise performance is required to be at least 10^{-11} m/s^2 rms over one day (equivalent to 7×10^{-15} at 60 s Doppler noise, consistent with the order of the gravity requirement).

The gravity measurements provide key information on the internal structure of Titan. Degree-two gravity coefficients will provide constraints on the global density, i.e., differentiation, and viscoelastic structure of the satellite, and especially the presence of a deep ocean. Higher degree gravity coefficients will provide constraints on the degree of compensation of the crust and the presence of lateral variations of density anomalies. The relative amplitude of the gravity coefficients at 1500 km altitude is presented in **Figure 2.4-19** with respect to the degree-zero field, and compared to the measurement capability using Ka- or X-band. This figure shows that Ka-band capability increases the measurement accuracy for Titan's gravitational field by one order of magnitude with respect to using only X-band.

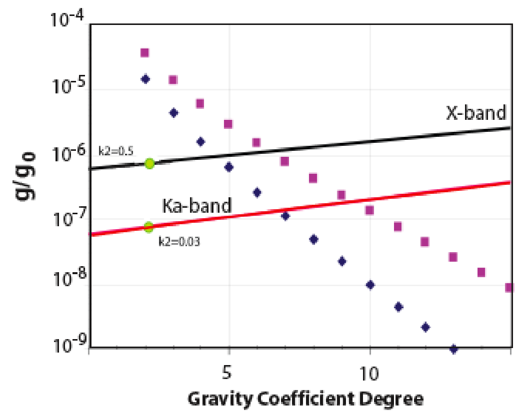


Figure 2.4-19. *Amplitudes of Titan's gravitational harmonics as a function of the surface gravity g_0 at 1500 km. The values can be compared with the accuracy predicted for Doppler-shift measurements in the X-band (black curve) and Ka-band (red curve). The blue dots were obtained assuming that all the gravitational anomalies are in the silicate core while the red points are for a model in which the gravitational anomalies are in the icy crust. The green points show the amplitude of the periodic part of the degree-two gravitational coefficients for different assumptions on Titan's interior (k_2 = 0.03 if there is no ocean; k_2 = 0.5 if there is a deep ocean.) The integration time is used for calculating this figure is 10 s, and the signal to noise ratio increases as the square root of the integration time. Lunar radio science studies (Konopliv et al. 1998) have been consulted in order to develop this figure and define the requirements for the RSA instrument.*

The system capability described above will enable a determination of Enceladus' degree-two gravitational coefficients, including the S_{22} coefficient that provides constraints on the gravity phase lag. These coefficients will yield constraints on the global density and visco-elastic structure of the satellite, as well as regional gravity profiles.

The inversion of the gravitational measurements relies on a good determination of the shape, which will be obtained from the measurements achieved with the TiPRA instrument. Measurements that allow the determination of higher-degree gravitational harmonics as well as higher resolution topographic measurements will enable the identification of large-scale, non-hydrostatic components, a necessary step in order to infer the global density and tidal Love numbers of the satellites from the degree-two gravitational data.

There are several mission requirements that stem from this experiment. For the gravity measurements at Titan the preferred Circular Orbit Phase height is 1500 km. Gravity data should be acquired while Titan is at different positions along its orbit, i.e., wide range of true anomalies, in order to characterize the tidal response of the satellite at degree-two.

At Enceladus, several gravity flybys with different latitudinal coverage would enable the de-correlation of the J_2 and C_{22} coefficients. Gravity signal must be acquired especially at closest approach, but also along long arcs, in order to optimize the de-correlation between the degree-two coefficients. Flybys for Enceladus at different true anomalies would yield information on the tidal response of the satellite, expressed through periodic components of the degree-two gravity coefficients, especially through the phase lag measurements.

Atmospheric occultations at Titan require geometries such that there is a line of sight from the spacecraft to the Earth propagating through the atmosphere.

2.4.4 Instrument and Mission Requirements

The measurement requirements of §2.3 place demands on both the instruments and the mission. The specific mission requirements are provided in the Traceability Matrix (**Table 2.3-1**), and the simultaneity of observations is discussed in §2.5.

Optimizing these requirements and noting these constraints has shaped the adopted nominal mission scenario.

Significant Saturnian system science is enabled by the two-year Saturn gravity-assist tour, which provides 16 Titan flybys and 7 close Enceladus flybys (2 at 1000 km, 1 at 300 km and 4 at 100 km) (**Figure 2.4-20**). The

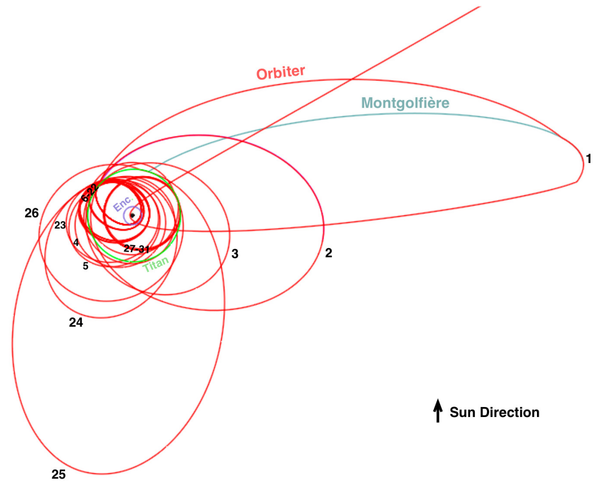


Figure 2.4-20. *Saturn Tour Phase with 16 Titan flybys and seven Enceladus flybys. The tour design provides a broad sampling of Saturn's maganetosphere and its interaction with Titan and Enceladus. The numbers refer to the orbit after SOI.*

planning payload will provide strong capability for accomplishing Saturn system science (see §2.5 for a brief summary) For Enceladus, this capability will greatly exceed that of Cassini by providing: superior mass spectroscopy of the Enceladus plume, higher resolution infrared imaging and spectroscopy of the surface, and radar altimetry of the active regions at the Enceladus south pole.

The Titan flybys of the Saturn Tour Phase give opportunities for the TSSM orbiter to exceed the Cassini data set with low altitude flybys giving a chance for *in situ* measurements deep in the Titan atmosphere. Other flybys provide opportunities for limb sounding. Several of the Titan flybys will sample the atmosphere from 720 km to 900 km altitude which in addition to yielding valuable science data will also help to better understand the atmosphere for aerobraking.

Following the Saturn Tour Phase, the spacecraft inserts into an initial 720 km by 15,000 km ellipse and will begin aerobraking in Titan's atmosphere. A two-month, Aerobraking Phase allows extraordinary scientific *in situ* measurements to be made that will be unavailable during the Circular Orbit Phase. Most notably, measurements can be made in the atmosphere down to 600 km altitude. The Circular Orbit Phase consists of a 1500 km

near-polar (85° inclination) circular orbit that begins with an descending node at a 11:30 am Local Saturn Time (LST) which rotates to 9:00 am by end of mission.

2.4.5 Data Acquisition Strategy

The mission consists of four phases: Interplanetary Cruise, Saturn Tour, Titan Orbit, and Decommissioning and Disposal. Valuable data will be acquired during each mission phase as numerous opportunities present themselves. Operations scenarios for all phases of the mission, including the relay of *in situ* data, are included in §4.6. This section discusses the drivers that shaped the operations scenarios. A plot of the total data volume acquired throughout the mission can be found on **FO-5**.

2.4.5.1 Saturn Tour Phase—Enceladus and Titan Flybys

When composing the operations scenarios for Enceladus and Titan flybys, the following questions were addressed:

1. Which instruments need to operate during the flyby for the mission to meet the Enceladus (or Titan) related science objectives?
2. What times during the flybys (i.e., what point in the flyby trajectory) are best for acquiring specific data sets?
3. Which instrument fields of view are co-aligned, and at which spacecraft attitudes can multiple instruments acquire their data simultaneously?
4. Is there enough power and data volume available for what is planned?

Saturn Orbit Insertion (SOI) will occur 9 years after launch and will mark the beginning of the Saturn Tour Phase. This phase will allow excellent opportunities to observe Enceladus and Titan, and the complex interaction between Titan and Saturn's magnetosphere. During the Tour Phase the spacecraft will perform 16 Titan and at least seven Enceladus flybys. Also, this 24-month period will mark the mission phase when the majority (if not all) of the Titan *in situ* data is relayed back to Earth.

Saturn Tour Flybys and Instrument Fields of View

The instrument orientations and fields of view were chosen to optimize data collection during the orbital phase. The remote sensing (RS) instruments and sounders are all nominally nadir-pointed and the fields and particles instruments all benefit from spacecraft ram pointing. This will also prove to be advantageous during the flybys of Enceladus and Titan by allowing groups of instruments to gather data simultaneously.

The majority of the science instruments will be fully operational for the critical hours surrounding the Titan and Enceladus flybys. This will be accomplished by putting the telecom system in standby mode and making use of the on-board rechargeable battery. For at least one of the low Enceladus flybys, telecom will remain operational so that measurements of the Enceladus gravity field and internal structure are taken using RSA.

For each low Enceladus and Titan flyby the spacecraft orientation will be optimized for the Remote Sensing (RS) and sounder instruments, except for the several minutes around closest approach. This period will be allocated to the fields and particles (F&P) instruments as they will characterize the chemistry of the Enceladus plume and Titan's atmosphere. The RS and F&P instruments will operate simultaneously throughout each Titan and Enceladus encounter. The F&P instrument data collection is optimized when the spacecraft +Y axis is aligned with the spacecraft ram direction. The RS boresights (-X) is 90° away from +Y. As the spacecraft nears closest approach, the angle between Enceladus and the spacecraft ram direction approaches and becomes 90° as

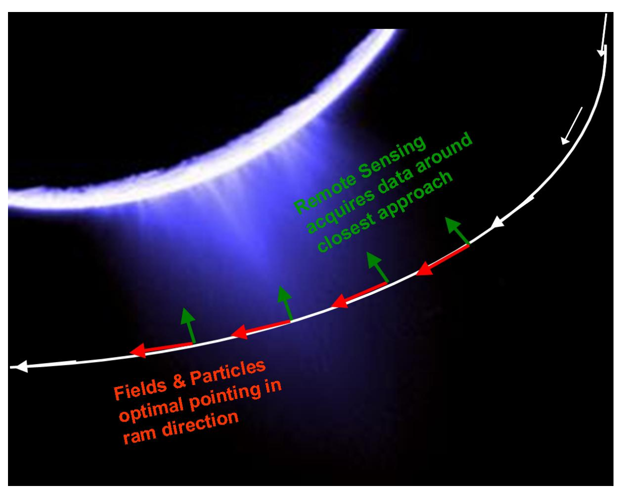


Figure 2.4-21. *Remote sensing and fields & particles instruments collect data simultaneously around closest approach.*

well. Hence both sets of instruments will gather data during the highly-valued closest approach period. See **Figure 2.4-21**.

Each Enceladus flyby will collect 15 Gb of science data that will be compressed to 3.75 Gb and played back over a 6.5 hour period that immediately follows the encounter. Each Titan flyby will collect 26 Gb of science data that will be compressed to 6.5 Gb and played back over two 7 hour downlink periods following each encounter. These downlink durations assume a conservative 140 kbps rate. Data rates for each orbiter instrument are shown in **Table 4.6-7**.

Also during the Saturn Tour Phase, the two *in situ* vehicles will perform their prime mission activities. The montgolfière will be released from the orbiter on approach to the first Titan encounter, and the lander will be release on the second Titan flyby. The extremely valuable data from these *in situ* vehicles will be recorded, sent to the orbiter when in view, and then relayed back to Earth. The entire data return strategy is discussed in §4.6.4.

2.4.5.2 Titan Orbit Phase

Aerobraking Phase

The Titan Orbit Phase begins with Titan Orbit Insertion (TOI) and a two-month aerobraking period. The ~170 aerobraking passes will yield data from deep in the atmosphere (possibly as low as 600 km altitude)—hundreds of km lower than the Cassini orbiter ventured.

When composing the operations scenarios for the Aerobraking Phase, the following questions were addressed:

1. Which instruments need to be operational during the *aerobraking* orbits for the mission to meet the related science objectives?
2. What times during the *aerobraking* orbit are best for acquiring specific data sets?
3. Which instrument fields of view are co-aligned, and at which spacecraft attitudes can multiple instruments acquire their data simultaneously.
4. Is there enough power and data volume available to accomplish the plan?

During the aerobraking orbits there will be near-continuous DSN coverage and therefore near-continuous operation of the telecom system. This is for two reasons: 1) Ground system knowledge of the spacecraft's orbital position and velocity, and 2) Radio Science will obtain a great deal of data regarding Titan's atmospheric and internal structure with gravity measurements and occultations.

During the Aerobraking Phase, the spacecraft attitude will be optimized for PMS and the other fields and particle instruments when the spacecraft is within Titan's atmosphere (i.e., below ~1500 km). In turn, the attitude will be chosen to benefit the RS instruments when above ~1500 km. TiPRA will not be operational during this phase of the mission.

Circular Orbit Phase

Once the spacecraft has settled into its 1500 km orbit, the powerful suite of instruments will carry out specific campaigns that will dramatically enhance our understanding of Earth's sister world.

When composing the operations scenarios for the Circular Orbit Phase, the following questions were addressed:

1. Which instruments should operate simultaneously based on science discipline?
2. What is the best duration of each cycle (i.e., number of orbits) for each set of instruments to operate?
3. Is there enough power and data volume available for each set of instruments to collect data on the same orbits?
4. Which instruments require sunlight, and which do not?

During the 20-month Circular Orbit Phase, the spacecraft will collect data continuously. Three different types of science campaigns, each designed to manage power and data rate, will be used to gather a wealth of information that will fully reveal this world and answer long-held questions about Titan's interior, surface, atmosphere, and interaction with Saturn's magnetosphere. Each campaign, or instrument combination, will be maintained for 16 days (one Titan revolution) and they are as follows:

1. Atmosphere and Ionosphere Campaign to identify and measure ions and neutrals globally for various Sun angles (PMS and MAPP).

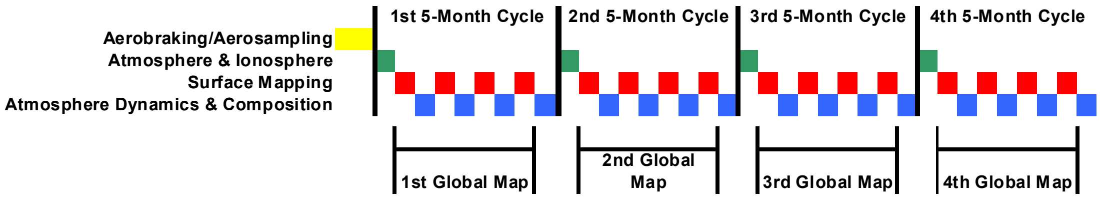


Figure 2.4-22. Campaigns are arranged in 5-month cycles comprising nine periods of 16-day campaigns.

2. Surface Map Campaign, during which a global map (in up to four colors) is obtained, to measure global altimetry with better than 10 m accuracy and perform surface spectroscopy (HiRIS, TiPRA, MAPP).
3. Atmospheric Dynamics and Composition Campaign to measure temperatures, composition, and winds, globally (TIRS and SMS).

Figure 2.4-22 illustrates how these campaigns may be used in succession to capture the Orbital-phase science objectives. The spacecraft will complete 80 orbits during each 16 day campaign.

Throughout the Titan Orbit Phase, the radio science instrument (RSA) will collect data at the DSN on every downlink. The operational scenarios are detailed in §4.6

Table 2.4-4 shows how the scientific investigations are accomplished throughout the mission timeline.

2.4.6 Science Operations and Planning

Science planning and operations for TSSM optimizes science return and data acquisition for the missions cruise, Saturn Tour and Titan Orbital Phases. Preliminary science sequences are pre-planned prior to launch to validate allocation of operational resources (power, telemetry, on-board storage and, for Interplanetary Cruise and Saturn Tour Phases, orientation of the nadir platform); to ensure that implementation fulfills the science requirements; to facilitate sequence refinement during orbital operations and to minimize operational complexity. The sequences are associated with three science campaigns (§2.4.5 and §4.6), each campaign managed and arbitrated by its interdisciplinary lead. The organization of the science planning team is shown in **Figure 2.4-23**. This organization, based on lessons learned in Cassini and Galileo, increases the time available to develop enhanced sequences for future cycles for each campaign and simplifies allocation of resources by partitioning them within specific and related science goals.

The science planning team includes the science teams, who are remotely located at their own institutions, the campaign planning leads, the remote and (mission) co-located sequence teams, a science system engineer and the project scientist. The science teams set the science strategy in the Project Science Steering Group (PSSG). This group consists of the instrument Principal Investigators (PIs) the interdisciplinary scientists (IDSs) and the Project Scientist. IDSs also serve as campaign leads, having arbitration authority within a given campaign. Remote sequence teams, nominally located at PI institutions, develop sequences for each campaign. The mission co-located sequence team provides support for the time-critical sequence activities and report to the science system engineer.

The rich scientific opportunities of the TSSM mission require that the sequence planning elements function efficiently during the Saturn Tour, Enceladus flybys, and Titan circular orbits (with periods of about 5 hours). This is the first time a combination of Cassini-like tour sequence development and MRO-like orbital sequence operations has been combined so particular attention has been given to the design of science planning for the TSSM mission to ensure that science planning does not drive operations costs.

The TSSM spacecraft design has two inherent advantages over Cassini for tour science planning: 1) data storage space is larger and 2) the remote sensing instruments FOV have a common (nadir) direction. These reduce considerably the number of resources that must be negotiated and the number of mutually exclusive options that must be arbitrated by the science teams. The level of resource contention for Titan Orbit Phase science planning is

Table 2.4-4. *Orbiter science accomplishments are distributed throughout the mission phases. In situ science, not shown here, is accomplished during the Saturn Tour Phase to achieve a balanced use of spacecraft resources.*

Science Objectives	Science Investigations	Saturn Tour Phase	Aerobraking Phase	Circular Orbit Phase (1st 5 months)
AO1: Determine how energy is deposited in the upper atmosphere to drive the chemistry and the escape rate of major atmospheric constituents.	**I1:** Quantify the deposition of radiation into Titan's atmosphere.	✓	✔	
	I2: Quantify the escape flux of elemental hydrogen, carbon, nitrogen.	✓	✔	✓
AO2: Characterize the relative importance of exogenic and endogenic oxygen sources.	**I1:** Quantify the flux of exospheric oxygen into the atmosphere.	✔	✓	
	I2: Quantify the flux of endogenic oxygen from the surface and interior.		✓	✔
AO3: Characterize the major processes controlling the global distribution of atmospheric chemical constituents.	**I1:** Characterize the major chemical cycles.		✓	✔
	I2: Determine the relative importance of global transport.		✓	✔
AO4: Characterize the atmospheric circulation and flow of energy and its variability on short-timescales.	**I1:** Determine the atmospheric thermal and dynamical state.			✔
	I2: Determine the impact of haze and clouds.		✔	✔
	I3: Determine the effects of atmospheric composition.			✔
	I4: Determine the effects of surface processes on meteorology.			✔
AO5: Characterize the amount of liquid on the Titan surface today.	**I1:** Quantify the total major-hydrocarbon (methane/ethane) inventory present in the lakes and seas.			✔
	I2 Determine the depth of the lake at the landing site			✔
AO6: Characterize the major processes transforming the surface throughout time.	**I1:** Determine the origin of major crustal features; correlate regional elevation changes with geomorphology and compositional variations.			✔
	I2: Characterize the origin of major surface features, including the effects of liquid flow, tectonic, volcanic, and impact events.			✔
	I3: Determine the internal magnetic signal of Titan		✔	
AO7: Determine the existence of a subsurface liquid water ocean.	**I1:** Determine crustal/subcrustal structure; reflectance of subsurface stratification.			✔
	I2: Determine if the crust is decoupled from the interior and the thickness and rigidity of the icy crust.			✔
	I3: Determine the induced magnetic field signatures in order to confirm subsurface liquid and place constraints on the conductivity and depth of the liquid		✓	✔
AO8: Determine the state of internal differentiation, whether Titan has a metal core and an intrinsic magnetic field, and constrain the crustal expression of thermal evolution of Titan's interior.	**I1:** Map interior structure of Titan.		✓	✔
	I2: Determine whether Titan has a dynamo.		✔	
BO1: Determine the processes leading to formation of complex organics in the Titan atmosphere and their deposition on the surface.	**I1:** Assay the speciation and abundances of atmospheric trace molecular constituents.		✔	✓
	I2: Assay the molecular complexity of the condensed phase.		✔	
	I3: Quantify the sources of chemical energy for atmospheric chemistry.	✔	✓	✓

KEY: AO1…AO4 = Goal A, Objective 1… Goal A, Objective 4; I1…I4 = Investigation 1 …Investigation 4,
✔ = Primary, ✓ = Secondary

Table 2.4-4. *Orbiter science accomplishments are distributed throughout the mission phases. In situ science, not shown here, is accomplished during the Saturn Tour Phase to achieve a balanced use of spacecraft resources, cont'd.*

Science Objectives	Science Investigations	Saturn Tour Phase	Aerobraking Phase	Circular Orbit Phase (1st 5 months)
BO1: Determine the processes leading to formation of complex organics in the Titan atmosphere and their deposition on the surface.	**I4:** Determine surface composition.			✓
BO2: Characterize the degree to which the Titan organic inventory is different from known abiotic organic material in meteorites.	**I1:** Assay the composition of organic deposits exposed at the surface, including dunes, lakes, seas.			✓
BO3: Characterize what chemical modification of organics occurs on the surface.	**I1:** Determine the roles of cratering and cryovolcanism in modification and hydrolysis of organics.			✓
	I2: Determine the importance of surface inorganic compounds as surface catalysts or doping agents.			✓
	I3: Quantify the sources of energy for surface chemistry and identify the sites where it may have been present.			✓
	I4: Quantify the amount of aerosols deposited on Titan's surface and their modification as they get buried.			✓
BO4: Characterize the complexity of species in the subsurface ocean.	**I1:** Determine whether evidence of sub-surface ocean species is present in cryovolcanic sites.			✓
BO5: Characterize bulk composition, sources of nitrogen and methane, and exchange between the surface and the interior.	**I1:** Determine whether carbon dioxide is primarily internally derived or photochemically produced.			✓
	I2: Determine whether methane is primordial or derived from carbon dioxide.			✓
	I3: Determine whether molecular nitrogen is derived from ammonia.			✓
	I4: Determine whether pockets of partial melt are present at depth.			✓
	I5: Determine the isotopic ratios of noble gases'		✓	
CO1: Determine how Titan's atmosphere evolves by virtue of its coupling to the Saturn magnetosphere and Titan's low gravity.	**I1:** Determine how energy is deposited in the upper atmosphere of Titan to drive the chemistry and the escape rate of major atmospheric constituents.		✓	
	I2: Determine the escape rates and mechanisms of major atmospheric species on Titan.		✓	
CO2: Infer the crustal and deep internal structure of Enceladus, including the presence of gravity anomalies, and the moon's tidal history.	**I1:** Test for the presence of crustal or deeper structures associated with Enceladus' internal activity, including an interface between a solid crust and a liquid layer, as well as partial melt pockets	✓		
	I2: Test for true polar wander on Enceladus.	✓		
CO3: Characterize the chemistry of the Enceladus plumes.	**I1:** Determine the composition of the plume, including isotopic abundances.	✓		
CO4: Understand the formation of the active region near the south pole, and whether liquid water exists beneath the area.	**I1:** Characterize the global and regional geomorphology of Enceladus' surface.	✓		
	I2: Determine whether thermal anomalies exist underneath the surface.	✓		
	I3: Determine the origin of the surface organic materials and its connection with interior reservoirs.	✓		
CO5: Identify and characterize candidate sites on Enceladus for future *in situ* exploration.	**I1:** Determine whether extrusion of water ice or liquid water has occurred recently.	✓		
	I2: Determine whether areas of extremely thin crust or exposed liquid within cracks exist.	✓		

KEY: AO1…AO4 = Goal A, Objective 1… Goal A, Objective 4; I1…I4 = Investigation 1 …Investigation 4,
✓ = Primary, ✓ = Secondary

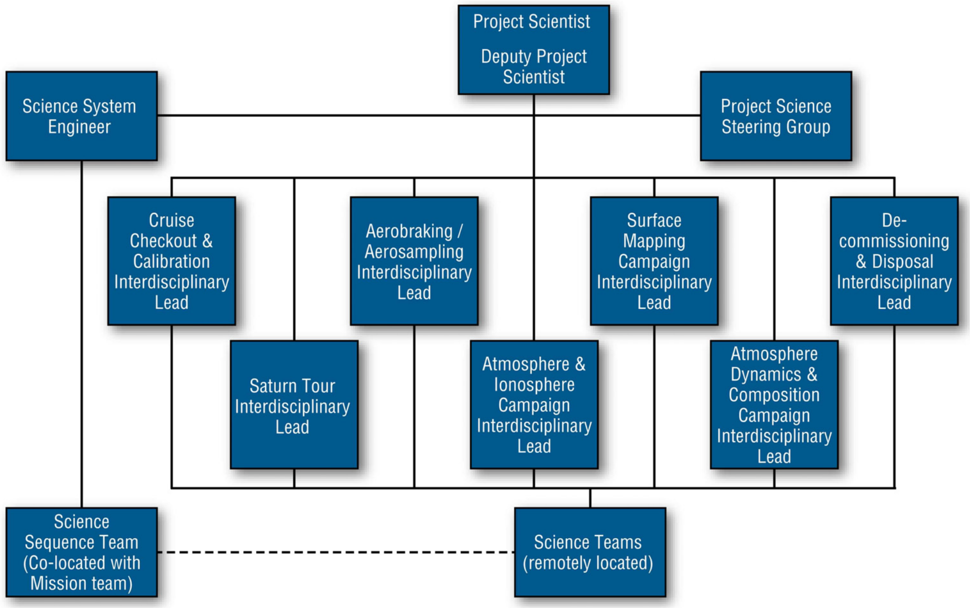


Figure 2.4-23. *The science planning team maximizes throughput and sequence adaptability by using a careful balance of remote and co-located planning teams and by establishing clear paths for decision-making that are grouped by related science goals.*

very similar to that for MRO, providing a high degree of heritage for utilizing planning paradigms, software, and applying lessons learned. Due to the Saturn Tour being focused on Titan, the number of planned observations is significantly less than Cassini. The sequence planning for encounters for those past missions required a lot of lead time and significant staffing. Many factors were responsible for these long lead times including large numbers of orthogonal science goals, scarce resources, and complex sequencing activities (such as obtaining mosaics) that require significant validation efforts. The potential sequencing costs of these factors were recognized early in the legacy missions, but tools and experience were too limited to avert incurring the costs. The Outer Planets Flagship effort undertook a joint study, led by APL, to capture operations lessons learned (Appendix K). Many of the recommendations are relevant to TSSM science planning and have been adopted as indicated in **Table 2.4-5**.

Specific advantages for the TSSM Saturn Tour Phase science planning include 1) a spacecraft design that is easier to operate (from a science instrument data-gathering perspective) than either Galileo or Cassini, 2) greatly improved ground and flight computational capability, 3) improved mechanisms for allocating and managing on-board data storage, 4) heritage software and lessons learned from two previous missions, and 5) science goals that are highly focused because Cassini results. Specific steps taken by TSSM to control the costs of science planning include early (prior to phase C) delivery and utilization of planning tools, pre-allocation of resources, pre-planning of sequences, and use of discipline-specific planning teams. It should be noted that early utilization of sequencing tools was planned for Galileo and Cassini as well. Those plans were not fulfilled primarily because the challenges associated with tool development were poorly understood and too many developments were required to allow early delivery of planning software. The experience and heritage from those missions have removed those obstacles to early delivery for TSSM. The Mission Operations Lessons-learned report for the OPFM emphasized the importance of using common sequencing tools. Delivery of tools and planning of sequences Pre-launch averts development of ad hoc tools that do not intercommunicate. It is recognized that some modifications will have to be made after launch to the sequences and resource allocations. However, active measures are planned to minimize

Table 2.4-5. *TSSM has an approach to conducting efficient science planning. TSSM is incorporating many of the recommendations of the report "Mission Operations Lessons Learned Study for the Next Outer Planets Flagship Mission" (Appendix K)—a study of four missions to find opportunities for improving mission operations. The study was lead by APL and including participants from APL, ARC, and JPL. The following table compares the recommendations that affect science sequence planning to the implementation used by TSSM.*

Cost Savings Recommendation	TSSM Approach
Reduce complexity of contention	Sequence is divided into topical campaigns, enabling true arbitration of priorities for science goals that are related. Campaign developments are lead by interdisciplinary scientists having decision authority
Co-locate mission planners	Orbital operations planners co-located
Streamline ITAR/TAA	Addressed aggressively from start of mission: TAA is already in place. Associate ITAR evaluation with the Science Operations Center (SOC).
Provide accessible central document repository	Implemented in the SOC
Conduct formal design of ops system early, with experienced operations personnel	Planned for phases A and early in Phase B
Incorporate SSR file system and pre- allocate SSR space	Prelaunch allocation of memory utilization, enforced with memory file system
Commonality of instrument and command interfaces	Uniform command dictionary; instrument orbital operations are non-interactive (except power, data volume –which are pre-allocated)
Set bounds on planning time, iterations	Cadence of campaign execution set bounds on planning timeline; Campaign Leads with decision authority simplify closure
Use integrated planning and sequencing tool.	Planned. TSSM requires the flight planning tools are available in phase CD to support early sequence planning. Early use achieved by adapting heritage software. This will also help focus flight teams on using a common tool set.
Have PI set priorities, sequence team implement.	Not implemented. Segmentation approach emphasizing related science, segment leadership, and science allocation of resources preferred for TSSM.
Incorporate resource modeling and flight constraints early in planning process	Required pre-launch
Use fast software simulation	Exercised pre-launch for sequence development.
Easy data access for sequence reviewers	Part of SOC

the scope of those changes. Preliminary sequences for both the tour and the orbital campaigns will be developed in Phase B to test that the spacecraft and ground systems designs and resources are consistent with low cost sequencing and to allow the science teams to become familiar with the sequencing tools. The final tour sequences will be developed after final tour selection about two years prior to SOI. The final orbital sequences will require only modest updates to the orbital sequences developed pre-launch. The operations cost savings achieved, relative to Cassini are substantial and are detailed in §4.11 and summarized in the table therein.

Orbital operations at Titan are very similar to MRO orbital operations at Mars, and TSSM science planning draws strongly on that heritage. TSSM has taken the additional step of dividing the orbital timeline into campaigns having specific related science goals. This enables a cogent allocation of resources since observations within a campaign can have a common scientific goal so that observational priorities can be arbitrated based on the focused science goal rather than a collection of unrelated, equal-priority science objectives. The campaign approach also enables establishing campaign leads with decision authority, making it possible to improve the timeliness, and to lower the cost of the science sequences. The science planning and operations system utilizes a combination of both remote and co-located elements to achieve cost-effective sequence adaptability during tour and orbital operations. The remote capability is required because of the length of mission duration and the wide geographical distribution of science team members. The remote capability allows instrument sequences to be designed, negotiated and monitored without frequent travel, while the co-located mission team can respond within the short timescales required, particularly for orbital ops. The remote and co-located teams are coordinated by investigation scientists and the science system engineer,

assisted by a support sequencing team (**Figure 2.4-23**). This approach allows timely modification of the pre-planned sequences to take advantage of new discoveries and to adapt to evolution of the mission plan and spacecraft while supporting the challenging response times that are often required by orbital operations.

The science planning sequences are developed jointly with the mission operations team. The mission operations team validates the sequence for correctness, checks compliance with flight and mission rules and spacecraft safety constraints, loads the sequence aboard the spacecraft, and verifies execution.

The science sequence development products and deliveries are available to the science teams through the Science Operations Center (SOC) to facilitate sequence development and to enable correlating sequence planning and operations with data receipt. Remotely located instrument teams generate the required configuration commands for their instrument. Data labels and a database link the uplink product to the downlink product.

Essential elements supporting remote sequence developments for campaigns include bi-weekly teleconferences and rapid remote access to flight and ancillary data and sequences (supported by the science operations center §2.4.7, and §4.5). Rapid sequence development and sequence verification is supported by co-location of essential personnel. The spacecraft team provides the information on the spacecraft state and attitude, resources available, and any potential conflicts that may be encountered. The co-located elements of the science operations team ensures that all instrument sequences meet science goals, are fully integrated, tested and successfully uplinked to the Flight System.

Science sequencing software includes programs to display sequence opportunities, track and facilitate display of correlated instrument and engineering data as well as ancillary data return, track utilization of scarce resources, and verify sequence commands (**Table 2.4-6**). TSSM uses adaptations of software from MRO and Cassini.

2.4.6.1 Science Planning

Science teams for each instrument perform analysis of the returned science products. The analysis will be used to support future data collection strategies and to guide the longer-range observation plan updates. The data include what is returned from both orbiter and *in situ* elements; in particular results from the orbiter might lead to a change in instrument operation on the montgolfière (e.g., more intensive imaging in a particular location) It is thus anticipated that extensive interaction among all the science teams will occur.

Table 2.4-6. *TSSM has a rich legacy of science planning tools from MRO and Cassini. These tools will be adapted to enable implementation and utilization of the science planning system prior to Flight System integration and test.*

	Mars Reconnaisance Orbiter	Cassini
Sequence Opportunity	MTT	ODD, SOAP, SOA
Correlated data return	Done by Instruments	Tightwad
Scarce resource utilization	Data Tracker	CIMS
Command Validation	SEQGEN	SEQGEN

The project science steering group (PSSG) is the coordinating body of scientists that sets up the overall science observation plan that will be used for the development and operation of the mission. Experience gained with Cassini shows that use of Discipline Working groups to cover different aspects of Titan, Enceladus and Saturn magnetospheric science is very effective. Because this mission will be much less conflict-driven that was Cassini with its 12 orbiter instruments with multiple field-of-view directions, it is anticipated that the science teams will spend far less time in conflict resolution and much more time in coordinated planning and in collaborative analysis of multiple data sets. The science observation planning process is designed to accommodate sequence evolution over the life of the mission as conditions change and spacecraft and instrument health change.

Instrument operations teams bridge the science teams and spacecraft operations. The science teams provide the direction for what instrument observations are to be baselined for the mission and science plans.

2.4.7 Data Analysis and Archiving

TSSM has a robust data delivery, analysis, and archiving plan that provide rapid delivery

of data to the science investigations and scheduled delivery of products to the archival Planetary Data System (PDS). The project will archive all data, however, the mechanism for doing that will be clarified after the NASA/ESA MOU is in place. The maximum volume of data acquisition occurs during orbital operations where the nominal 140 kbps downlink rate with 60% duty cycle delivers 7.3 Gb/day or about 4.4 Tb during 20 months of orbital operations. It is straightforward to routinely handle this data volume with current storage and network technology.

The project Ground Data System (GDS) generates level 0 data (validated and bested telemetry packets containing data numbers (DN)) that includes instrument engineering data (made available in a separate stream to facilitate near-real-time monitoring of instrument health), spacecraft attitude and timing information, and instrument data. The level 0 spacecraft and instrument data are routed to the Navigation Ancillary Information Facility (NAIF), where the geometry, timing, and event (SPICE) kernels are formed; and to the Multimission Image Processing Facility (MIPF) where the multiple downlink streams (e.g., dual station receipt, real-time and playback streams) are merged, catalogued, associated with ancillary data and converted to level 1 (i.e., data converted to engineering units and optionally calibrated and projected) instrument Experiment Data Records (EDRs). For the *in situ* elements, the level 0 packets are sent to ESA for processing and routing—a routing similar to that used for data from ESA's Huygens Titan Atmosphere Probe (see §4.5.2.4).

The scientific investigations can access their raw data very soon after earth receipt and EDRs and ancillary data on a schedule consistent with the data processing required to generate the higher level products at the Science Operations Center.

The project is responsible for ensuring the science investigations deliver their calibrated data with PDS labels for archival to the appropriate PDS nodes 6 months after earth receipt of the data. The *in situ* experiments will also deliver their data to PDS (similar to the approach used by Cassini-Huygens). It is anticipated the majority of data analysis will be performed at facilities provided by the science investigations (**Figure 2.4-24**).

2.5 Opportunistic Science with TSSM

Although the focus of this mission is stipulated by NASA to be Titan and the Saturn system science that relates to Titan (such as Enceladus and the magnetosphere), there are many prospects for opportunistic science during Saturn orbit insertion and the two-year Saturn system tour prior to insertion into Titan orbit, and even a few during the Titan orbital mission. Some of these include unique ring science during Saturn orbit insertion and during the Saturn system tour, Saturn atmospheric science during a Saturn season different from Voyager and Cassini, as well as possible flybys of other icy satellites besides Enceladus. These options are briefly discussed below and will be explored in more detail in Phase A.

2.5.1 Ring Science during Saturn Orbit Insertion

Cassini made some astounding discoveries about Saturn's rings as it looked down on the unlit rings just after the completion of its Saturn Orbit insertion (SOI) maneuver. Cassini's cameras photographed the A and C rings with at least ten times higher resolution than ever before or since, about 100 m in the A ring and skipped over the dark B ring. The *in situ* instruments detected a tenuous ring "atmosphere" of water decomposition products and evidence for micrometeoroids impacting the rings as Cassini flew over them.

From Cassini occultations, it is now known that the A ring is composed primarily of *gravitational wakes*, long particle clumps on the order of 20–50 m wide in the A ring (Colwell et al. 2006), smaller than anything that could be resolved by the Cassini cameras, especially on the unlit side of the rings. In the B ring clumping occurs from viscous overstability waves that are estimated to be about 140 m in width (Colwell et al. 2007). These observations produced fundamental advances in our understanding of ring structure yet their physical shape is still unknown.

TSSM's Saturn orbit insertion trajectory is on the lit side of the rings and is three to four times closer to the B and C rings than Cassini's SOI trajectory. For the outermost A ring, TSSM is only 1,000 km away, about seven times closer than Cassini, providing near-IR resolution better than 20 m. The closer flyby distance, combined with the lit-side viewing of the rings, opens up the possibility for direct

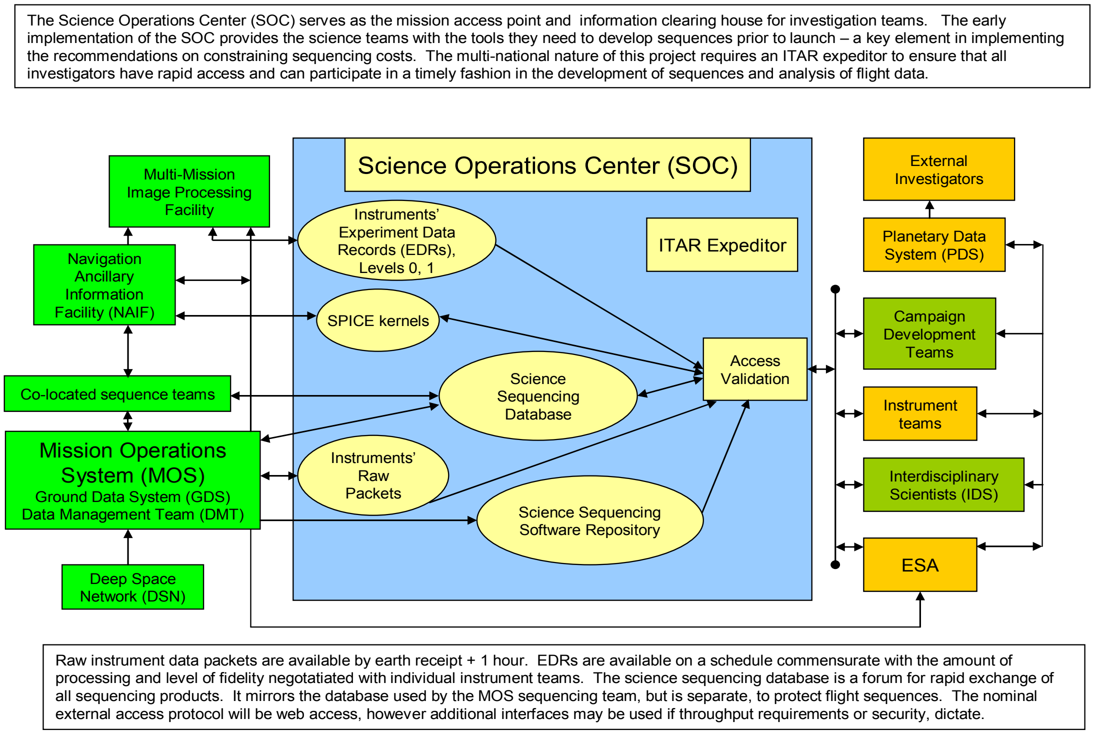


Figure 2.4-24. *Process for science data distribution (See **Figure 4.5-1** for functional role of SOC in the ground system).*

imaging of the A and B ring gravitational wakes, and would represent a huge step forward in our understanding the dynamics and composition of this complex system. The closer flyby distance will also enhance *in situ* measurements of the ring atmosphere.

2.5.2 Saturn Atmospheric Science

Cassini near-IR observations of Saturn's atmosphere reveal a planet as complex and dynamic as Jupiter (e.g., Baines et al. 2008b; Del Genio et al. 2008). Imaging the planet at 5 µm wavelength, the Cassini Visual Infrared Mapping Spectrometer (VIMS) discovered a panoply of deep cloud features beneath the planet's ubiquitous cover of upper-level hazes. Most features—silhouetted against the glow of Saturn's internal heat—occur near the 2–3 bar level, hinting tantalizingly at unusual dynamics in the atmosphere below. Most of these features seem to be found only on Saturn, not on Jupiter or any other outer planet.

Unusual cloud features observed are transient in some cases, persistent in others. Large (~8000 × 4000 km) transient plumes in the equatorial region likely produce the enhanced upper-level hazes there. Discrete thunderstorm-generated clouds in the upper troposphere of Saturn are of two distinct types: bright clouds similar to some found on Jupiter and near-IR-dark clouds that reveal materials dredged up from deep within the atmosphere by thunderstorms. Persistent features include annular clouds ("donuts") at temperate northern latitudes, a "string of pearls" of approximately two dozen regularly spaced, westward-drifting cloud clearings extending over one quarter of Saturn's circumference near 33 degrees north latitude, and the solar system's largest and most powerful vortices at both poles (Baines et al. 2008a; Dyundina et al. 2008), with the perplexing hexagonal feature around the north pole (Baines et al. 2008a). The string-of-pearls and 47° annular cloud are unusually steadfast features that drift westward with the largest retrograde speeds yet observed on Saturn suggesting unusual dynamical mechanisms that form and maintain them.

Observations of Saturn by TSSM could provide new information on all of these un-

usual features at a season different from that observed by Cassini. The extension of TSSM's near-IR detector to nearly 6 µm (compared to 5 µm for Cassini) could allow deeper probing of Saturn's atmosphere. Such new observations would provide additional fundamental information on the 3-D dynamical nature and composition of the materials involved in these meteorological/circulatory phenomena.

2.5.3 Additional Icy Satellite Flybys

The icy satellites of Saturn are unexpectedly diverse, ranging in size from tiny ring-moons only a few km in diameter to the largest icy satellite, Rhea, ~1500 km in diameter. Multiple spectral features of the dark material on icy Saturnian satellites are common to Phoebe, Iapetus, Hyperion, Epimetheus and the F-ring, implying the material has a common composition throughout the Saturn system. However, the exact composition of the dark material remains a mystery, except that bound water and, tentatively, ammonia and nano-iron are detected (Clark et al. 2008a). Exact identification of composition requires additional laboratory work and higher spectral resolution by a future mission. Some of those spectral features occur in the wavelength range of the Titan 2 and 2.7 µm windows, so a Titan-specific imaging spectrometer could also provide important and unique data to solve remaining mysteries on the icy satellites.

Currently the only sources of data on the internal structure of icy satellites other than Titan are very low-resolution models from gravity field measurements and hints at layering and compositional inhomogeneity seen in crater walls by UV, IR, and visible imaging. TSSM's planning payload includes a ground-penetrating radar instrument that could provide structural information to a depth of many km (up to 50 km at Enceladus). Such information has the potential to revolutionize our understanding of the formation and evolution of icy satellites, and of the mechanisms driving activity, if present, at Dione.

During the two-year Saturn tour TSSM might fly close to some of Saturn's other icy moons. Observing these bodies with TSSM's instrumentation, especially in the near-IR and with ground-penetrating radar, might lead to discoveries of new aspects of these bodies.

2.6 Synergy between the Orbiter and *In Situ* Elements

The scientific rationale and planning payload for the ESA-contributed in situ elements is detailed in Appendix J. The model instruments for the montgolfière are shown in **Table 2.6-1** and the lake lander in **Table 2.6-2**.

Table 2.6-1. *Model instruments in the planning payload on the Montgolfière which will circumnavigate Titan at ~10 km altitude in the equatorial region.*

Instrument	Description
BIS	Balloon Imaging Spectrometer (1–5.6 µm) with mapping capabilities for troposphere composition and surface composition at 2.5 m resolution.
VISTA-B	Visual Imaging System including 2 wide angle cameras with stereo capabilities and one narrow angle camera for detailed geomorphology at 1 m resolution.
ASI/MET	Atmospheric Structure Instrument and Meteorological Package to record atmosphere characteristics and determine wind velocities in the equatorial troposphere.
TEEP-B	Titan Electronic Environment Package to measure the electric field in the troposphere (0–10 kHz) and determine the connection with weather.
TRS	> 150 MHz radar sounder for the detection of shallow reservoirs of hydrocarbons, depth of icy crust and better than 10 m resolution stratigraphic of geological features.
TMCA	Mass spectrometer for analysis of aerosols and determination of noble gases concentration and ethane/methane ratios in the troposphere
MAG	Magnetometer to separate internal and external sources of the field and determine whether Titan has an intrinsic and/or induced magnetic field.
MRST	Radio Science using spacecraft telecom system

Table 2.6-2. *Model instruments in the planning payload for the lake lander.*

Instrument	Description
TLCA	Titan Lander Chemical Analyzer with a suite of mass spectrometers using gas chromatography to perform isotopic measurements, determination of the amount of noble gases and analysis of molecules up to 10,000 Da.
TiPI	Titan Probe Imager using Saturn shine and a lamp to provide context images and views of the lake surface.
ASI/MET-TEEP	Atmospheric Package including electric measurements capabilities to characterize the atmosphere during the descent and at the surface of the lake and to reconstruct the trajectory of the lander during the descent.
SPP	Surface properties package characterizing the physical properties of the liquid, the depth of the lake and the magnetic signal at the landing site.
LRST	Radio Science using spacecraft telecom system

Table 2.6-3 (located at the end of §2.7) illustrates how the scientific investigations are captured by the three elements of the mission: the orbiter, lake lander, and the montgolfière. The JSDT deliberately populated each element with instruments capable of achieving optimal scientific return in their particular operating environment, while eliminating unnecessary redundancies. Some of the *in situ* element instruments provide ground truth data for the orbiter while the orbiter instruments provide context for the lander and montgolfière scientific investigations. For example, magnetometry aboard the montgolfière and lake lander allow for sensitive field measurements beneath Titan's screening ionosphere, while orbiter magnetometry allows one to separate the inducing from the induced fields. It is also a pre-requisite in order to study Saturn's magnetosphere and the plasma interaction with Titan, in particular the remarkable interaction between Titan's ionosphere and Saturnian magnetosphere, in which the former holds Titan's ionosphere carries an imprint of the Saturnian field while in the magnetosphere, only to have this swept away periodically by the solar wind (Bertucci et al. 2008).

The *in situ* magnetometry to determine the presence of induced or permanent fields provides one type of constraint on the interior, while the radio science investigation aboard the orbiter provides complementary constraints through the gravitational moments and tidal response of the satellite. An analogy here is to the Juno mission in which sensitive magnetometry and radio science gravitational measurements will be used together to diagnose the state of the Jovian interior. The possibility of an ESA-contributed *in situ* measurement of the tidal response of the surface over a Titan day from a heat shield mounted transponder landed on the surface provides yet another, more direct means, of measuring tidal response. **Table 2.6-4** (located at the end of §2.7) gives the scientific investigations and the measurement requirement and approaches for the Geosaucer. Appendix J provides more detail.

In other cases, the *in situ* instruments perform unique measurements that are highly synergistic with measurements made other platforms. For example, the lake lander's chemical analysis package is intended for a general analysis of the organic molecules dissolved into the lakes. As noted above, laboratory studies demonstrate that hydrocarbons and some nitriles dissolve in liquid ethane-methane to an extent (Dubouloz et al. 1989; Tiffin et al. 1979) that makes them detectable with a mass spectrometer of the dynamic range proposed here. Because of sedimentation from the atmosphere and transport by winds of small organic particles previously deposited on the surface, the lakes provide a unique opportunity to assay material from around Titan. Further, the proposal that argon and other noble gases have been swept from Titan's atmosphere by aerosols (Jacovi and Bar-Nun 2008) makes imperative the testing of the lakes for dissolved noble gases—also soluble at levels detectable by the mass spectrometer (Clever et al. 1957). Measurement of the isotopic abundances of the various constituents provides a powerful test of models for the origin of Titan's methane and nitrogen as well as discernment of the chemical pathways by which these have been transformed into other organic compounds.

Thus, the primary science objectives for the chemical analyzer on the lake lander are to determine the: 1) inventory of soluble products in the lake over a mass range of 1 to 500 Da, 2) isotopic ratios of key organic species, 3) noble gas mixing ratios and their isotopic ratios, and 4) atmospheric composition—aerosols and gases. The measurement requirements and the associated data product requirements are considered for each of these objectives in turn.

1. Organic inventory: The driving measurement requirement in this case is to cover a mass range from 1 to 500 Da of organics soluble in a mare of liquid methane/ethane with sufficient separation/resolution required to separate nitriles from hydrocarbons with similar masses, i.e., HCN versus C_2H_4. *Objective 1* relies on the acquisition of Gas chromatography × Gas Chromatography Mass Spectrometry data, which in raw form is a serial data stream of mass spectra obtained at a rate of 200 Hz over the course of a 30 min gas chromatography run. This data set allows full 3-D analysis (the data cube) of the organic makeup of the volatile organics—one dimension for the mass spectra and two dimensions for the retention plane of the gas chromatograph—one axis that represents volatility and

the other expressing molecular polarity. Each data cube in this mode requires ~1.5 GB of storage (400,000 mass spectra, each 1024 × 32 bits) so that considerable data compression and editing of the data cube will be necessary. The reduced data products are a retention plane image and a set of mass spectra. The retention plane image is a representation of the total ion count as a function of the retention times. This data is formed into a two-dimensional array (400,000 × 16 bits = 6.4 Mb). The summary mass spectra are spectra of particular mass peaks in the retention plane (~30 peaks—30 × 10 × 1032 × 32 bits = 10 Mb). The peaks are autonomously selected by the flight software according to criteria included in the operations table. In addition, a time integrated summary mass spectrum (1032 × 64 bits = 0.7 Mb) will also be created with a run time of 30 min.

2. Isotopic ratios of key species: Once key mass peaks are determined from the organic inventory (1 above), then the GC × GC run must be repeated three more times to determine the stable isotopes of C, N, and O by diverting the 30 peaks into a combustion oven and subsequently into an isotopic ratio mass spectrometer with an anticipated accuracy fro isotopic ratios of 0.1 per mil. This requires (3 × (30 × (4 × 60 × 32 bits)) = 0.7 Mb) with a run time of 90 minutes.

3. Noble gas mixing ratios: The driving measurement requirement in this case is the dynamic range and sensitivity of the instrument. The sensitivity must extend over 8 orders of magnitude and the noble gas enrichment cell provides an additional 2 orders of magnitude. The gas sample will be acquired for 30 min and sampled as a full mass spectrum for 5 min at a rate of 0.1 Hz. This will be repeated 5 times over the course of the mission. The data volume is 5 × (30 × (1032 × 32bits)) = 4.65 Mb. The additional run time is 20 minutes

4. Atmospheric composition: The atmospheric composition is acquired by a direct sample acquired over 5 min 4 times during the mission, which again results in a 4.65 Mb sample and an additional run time of 20 min.

Since objectives 1) and 2) are of highest priority this process will be repeated a second time resulting in 17.8 Mb of data and an additional 2 hours of run time.

The connection to the orbiter is profound. The orbiter will directly sample organics in a region of formation high above the surface—where magnetospheric particles precipitate into the atmosphere forming a broad suite of polymers—over an altitude range of hundreds of kilometers during the aerobraking. It will also remotely sense organics formed below 600 km, down to the surface, over a wide range of latitudes. This provides an opportunity to assess the history of organics from their formation high in the atmosphere to their deposition in the lakes. Taken with the aerosol analyzer on the montgolfière, this connection is extraordinarily powerful—the first opportunity for a comprehensive sampling of Titan's organic chemistry from top to bottom.

Finally, the chemical analyzer provides an opportunity—without modification of the hardware or analysis protocol—for a test of the hypothesis, discussed in §2.2, that the ethane/methane lakes on Titan could be a suitable medium for an exotic form of organic life (Baross 2007), or at least a self-sustaining organized chemistry that could be called primitive or proto-life, that uses not water but liquid hydrocarbons. Regardless of how one regards this speculative notion, the lake lander has the instrumentation to provide a first cut assessment of this hypothesis.

This will be done by looking for the following:

- Presence of complex organic compounds including polymeric compounds of high molecular weight of 1,000 or greater. This characteristic is based on the assumption that all life regardless of origin would have a macromolecular machinery and would be complex compared with the abiotic background. The mass spectrometer will be well capable of detecting complex organics; the GC × GC will enable diagnostic identification of the organic species contributing to the mass spectrogram.
- Isomeric selectivity: Because enzymes strongly alter the outcome of organic chemical reactions, preferentially generating some compounds while destroying or suppressing others, a plot of the abundance of organic compounds versus molecular

weight and polarizability will look very different for biologically mediated samples than for those that are abiotic. The same may hold true for very primitive forms of life relying on catalysts that are simpler than enzymes. A pattern of abundance versus molecular weight will be obtainable with the GCMS, indeed even with the mass spectrometer alone if the living or proto-living system were highly selective. The ability of GC × GC to delineate molecular structure (it is not just molecular weight which correlates with volatility one also gets polarizability, which is very structure dependent) makes it a very powerful tool for pattern recognition.

- Homochirality, based on the assumption that all life irrespective of its chemistry would employ well-structured, chiral, stereochemically pure macromolecules. To fulfill the intricate functions of the molecular machinery of life, any organism regardless of origin would have to distinguish between molecules of different handedness and select a preferable handedness, thus enriching one enantiomer of chiral compounds. The GCMS will be provided with the capability to discriminate handedness.
- Isotopic fractionation toward the lighter biogenic elements. On Earth, it is observed that organisms prefer lighter isotopes and thus produce as a net effect distinct fractionation rates of isotopic ratios in biological elements. Thus, this search parameter is based on the assumption that life elsewhere would also prefer isotopes that require less energy to process.
- The camera system will illuminate the surface of the liquid and be able to assess any time dependent changes. While macroscopic organisms are highly unlikely, Carl Sagan pointed out during the Viking mission that the camera provides a way to rule in or rule out such a possibility in place of an a priori dismissal.

In the case of isotopic enrichment and enantiomeric excess it is not proposed to quantify the effect expected—even on Earth isotopic evidence for ancient life is faint and the range of carbon enrichments large. A significant result would be one in which several of the above indicators differ from what would be expected in an abiotic organic environment. That the lake lander can test for life in these varied ways is a bonus obtained from the organic rich nature of Titan's surface and the consequent requirement that instruments be designed to analyze the organic compounds. Put simply, a first search for life in the lakes comes almost for free.

Imaging on the orbiter will provide a factor of 10 or more improvement over the Cassini orbiter and global coverage. By itself this is a fundamental advance over what Cassini-Huygens could do (Huygens having covered a very small area in detail). The unique feature of the montgolfière is its ability to circumnavigate the globe at low altitudes (10 km) so as to all very high resolution imaging of a broad sweep of terrains. The montgolfière camera will perform stereo panoramic and high-resolution geomorphological studies at resolution of better than 10 m per pixel, with selected areas at a meter per pixel with a narrow angle camera. Several thousand images at least will be returned to the orbiter for relay to the Earth, over hundreds of thousands of square kilometers, a non-negligible fraction of Titan's surface area. Since resolutions among the three cameras vary by an order of magnitude or less, the systems—orbiter and montgolfière wide-angle and narrow-angle—are almost ideally matched to provide scene context from orbiter to the montgolfière wide-angle camera, and then from the wide- to the narrow-angle camera.

The list of applications of this well-nested set of images is too large to enumerate fully, but an outstanding example is application to fluvial erosion. From Cassini orbiter radar images, broad valleys are seen at 300–500 m resolution, but there is no information as to the density of smaller-scale fluvial features. Is there higher order branching of the broad valleys into dense networks of fluvial features? The Huygens site shows a well developed fluvial system in the hills, but the radar data in that location are too coarse in resolution (2 orders of magnitude) to show any context in terms of larger scale drainage systems. The TSSM orbiter plus montgolfière imaging systems will trace fluvial drainage systems from the largest channels down to Huygens-scale features, providing the first possibility to determine processes of origin and calculate

how much methane has flowed across various parts of Titan's surface.

Altimetry and crustal sounding from the orbiter will be complemented by much more detailed stratigraphic profiling from the montgolfière. Global imaging and sounding coverage from the orbiter will allow the montgolfière's crustal profiling to be placed on a regional and global scale context. This provides a well-constrained assessment of crustal structure, including features arising from tectonic, cryovolcanic, impact, and sedimentary processes, and their distribution.

Measurements of the chemical processes ongoing from beyond the exobase down to the stratosphere by the orbiter will be continued downward by *in situ* measurements in the troposphere from montgolfière, and in one of the large seas from the lander. The latter's very sophisticated *in situ* chemical laboratory will provide information on dissolved products whose origins in the high atmosphere can be directly assessed by mass spectrometric measurements from the orbiter. The ability to "taste" and "smell" (reasonable sensory analogs of GC and MS), in the lake, material whose genesis the orbiter "smelled" 1000 km above the surface, represents one of the best correlative compositional measurement opportunities in the history of planetary exploration (and goes well beyond what was possible with Cassini-Huygens).

Near-infrared spectroscopy of the surface from the montgolfière will provide high resolution views of the composition from reflectance spectroscopy across the organic (or organic-coated) dunes, outwash planes and channels, impact craters and putative cryovolcanic features, and the enigmatic circular features of the low latitudes. This will complement the *in situ* analyses of dissolved organics from the lake lander. However, the limited field of view of the near-IR spectrometer on the montgolfière requires that regional-scale spectrometry place those data in context—and this will be accomplished by the orbiter. Other examples of synergies can be seen in **Table 2.6-3**.

2.7 Primacy of the Orbiter

The synergies between the orbiter and the *in situ* elements should not obscure the fact that the orbiter is central to this mission and, indeed—should ESA decide not to participate—stands by itself as an outstanding Flagship-class mission. The orbiter will be well capable of addressing the fundamental issues about Titan that Cassini-Huygens data have defined, with its carefully selected and focused planning payload or equivalent instruments. The instrument suite is comprehensive enough to do imaging, subsurface sounding, chemical analysis, meteorological and compositional sounding, internal structure measurements, interaction of Titan with the ambient Saturnian and solar wind plasma, and compositional, imaging, and subsurface sounding of Enceladus.

With regard to payload, it is important to recognize that "more is better" is fallacious for a mission whose science goals are comprehensive mapping over a large area and whose mission lifetime is constrained by the overall mission scope (lifetime) and cost. For example, over the nominal mission lifetime, with the planning payload selected it will be possible to fully map the illuminated part of Titan's surface at better than 50 m resolution and obtain global topography, while conducting chemical sampling and atmospheric sampling at a range of latitudes and times of day, mapping internal structure, and sounding the subsurface—without significant conflicts among instruments. The orbiter is a powerful tool for addressing all the major science goals identified for this mission, for Titan, its Saturnian environment, and Enceladus.

The orbiter mission is the result of a carefully deliberative process, lengthy in its origins in the TE07 study, participatory in the extensive exposure it received at the Paris-Meudon and Pasadena workshops, and up-to-date in its responsiveness to the discoveries of Cassini-Huygens through the end of the prime mission (July 1, 2008). This study demonstrates that an exciting Titan Saturn System Mission that explores two worlds of intense astrobiological interest can be initiated now for the price of a single mission.

Table 2.6-3. TSSM mission elements are highly complementary.

Mission Goals	Science Objectives	Science Investigations	Orbiter	Montgol-fière	Lake Lander
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O1:** Determine how energy is deposited in the upper atmosphere to drive the chemistry and the escape rate of major atmospheric constituents.	**I1:** Quantify the deposition of radiation into Titan's atmosphere.	X		x
		I2: Quantify the escape flux of elemental hydrogen, carbon, nitrogen.	X		x
	O2: Characterize the relative importance of exogenic and endogenic oxygen sources.	**I1:** Quantify the flux of exospheric oxygen into the atmosphere.	X	x	x
		I2: Quantify the flux of endogenic oxygen from the surface and interior.	X		X
	O3: Characterize the major processes controlling the global distribution of atmospheric chemical constituents.	**I1:** Characterize the major chemical cycles.	X		x
		I2: Determine the relative importance of global transport.	X		
	O4: Characterize the atmospheric circulation and flow of energy and its variability on short-timescales.	**I1:** Determine the atmospheric thermal and dynamical state.	X	X	x
		I2: Determine the impact of haze and clouds.	x	X	
		I3: Determine the effects of atmospheric composition.	X	X	
		I4: Determine the effects of surface processes on meteorology.	X	X	
		I5: Determine the exchange of momentum, energy and matter between the surface and atmosphere and characterize the planetary boundary layer.		X	x
		I6: Determine the connection between weather, ionosphere, and electricity.		X	x
	O5: Characterize the amount of liquid on the Titan surface today.	**I1:** Quantify the total major-hydrocarbon (methane/ethane) inventory present in the lakes and seas.	x		X
		I2: Determine the depth of lake	x		X
		I3: Determine surface composition that might reveal the presence of liquids		X	
		I4: Determine the nature of precipitation responsible for the formation of valley networks in the equatorial regions.		X	
	O6: Characterize the major processes transforming the surface throughout time.	**I1:** Determine the origin of major crustal features; correlate regional elevation changes with geomorphology and compositional variations.	X	x	
		I2: Characterize the origin of major surface features, including the effects of liquid flow, tectonic, volcanic, and impact events.	X		
		I3: Determine the internal magnetic signal of Titan	x	X	x
		I4: Detect and measure the depth of shallow subsurface reservoirs of liquid (hydrocarbons).	x	X	
		I5: Determine the subsurface structures and constrain the stratigraphic history of dunes.		X	

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4,
X = Primary, **x** = Secondary

Table 2.6-3. *TSSM mission elements are highly complementary, cont'd.*

Mission Goals	Science Objectives	Science Investigations	Orbiter	Montgol-fière	Lake Lander
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O7:** Determine the existence of a subsurface liquid water ocean.	**I1:** Determine crustal/subcrustal structure; reflectance of subsurface stratification.	X		
		I2: Determine if the crust is decoupled from the interior and the thickness and rigidity of the icy crust.	X	x	
		I3: Determine the induced magnetic field signatures in order to confirm subsurface liquid and place constraints on the conductivity and depth of the liquid	x	X	x
	O8: Determine the state of internal differentiation, whether Titan has a metal core and an intrinsic magnetic field, and constrain the crustal expression of thermal evolution of Titan's interior.	**I1:** Map interior structure of Titan.	X		
		I2: Determine whether Titan has a dynamo.	x	X	
		I3: Quantify exchange between interior and atmosphere.		x	X
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O1:** Determine the processes leading to formation of complex organics in the Titan atmosphere and their deposition on the surface.	**I1:** Assay the speciation and abundances of atmospheric trace molecular constituents.	X	X	x
		I2: Assay the molecular complexity of the condensed phase.	x	X	
		I3: Quantify the sources of chemical energy for atmospheric chemistry.	X	x	x
		I4: Determine surface composition.	x	X	
		I5: Determine the composition of organics in the lake and the isotopic ratios of major elements.			X
	O2: Characterize the degree to which the Titan organic inventory is different from known abiotic organic material in meteorites.	**I1:** Assay the composition of organic deposits exposed at the surface, including dunes, lakes, seas.	X	x	X
		I2: Determine the chirality of organic molecules.			X
		I3: Determine the location and the composition of complex organics in and around impact craters in equatorial regions.		X	
	O3: Characterize what chemical modification of organics occurs on the surface.	**I1:** Determine the roles of cratering and cryovolcanism in modification and hydrolysis of organics.	X	x	x
		I2: Determine the importance of surface inorganic compounds as surface catalysts or doping agents.	x	X	
		I3: Quantify the sources of energy for surface chemistry and identify the sites where it may have been present.	X		
		I4: Quantify the amount of aerosols deposited on Titan's surface and their modification as they get buried.	X		
	O4: Characterize the complexity of species in the subsurface ocean.	**I1:** Determine whether evidence of sub-surface ocean species is present in cryovolcanic sites.	X	x	

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4,
X = Primary, **x** = Secondary

Table 2.6-3. *TSSM mission elements are highly complementary, cont'd.*

Mission Goals		Science Objectives	Science Investigations	Orbiter	Montgol-fière	Lake Lander
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?		**O5:** Characterize bulk composition, sources of nitrogen and methane, and exchange between the surface and the interior.	**I1:** Determine whether carbon dioxide is primarily internally derived or photochemically produced.	X		X
			I2: Determine whether methane is primordial or derived from carbon dioxide.	x	x	X
			I3: Determine whether molecular nitrogen is derived from ammonia.	x	x	X
			I4: Determine whether pockets of partial melt are present at depth.	X	x	
			I5: Determine the isotopic ratios of noble gases'.	x		X
Goal C: What can be learned from Enceladus and Saturn's magnetosphere about the origin and evolution of Titan?	**Saturn Magnetosphere**	**O1:** Determine how Titan's atmosphere evolves by virtue of its coupling to the Saturn magnetosphere and Titan's low gravity.	**I1:** Determine how energy is deposited in the upper atmosphere of Titan to drive the chemistry and the escape rate of major atmospheric constituents.	X		
			I2: Determine the escape rates and mechanisms of major atmospheric species on Titan.	X		
	Enceladus	**O2:** Infer the crustal and deep internal structure of Enceladus, including the presence of gravity anomalies, and the moon's tidal history.	**I1:** Test for the presence of crustal or deeper structures associated with Enceladus' internal activity, including an interface between a solid crust and a liquid layer, as well as partial melt pockets	X		
			I2: Test for true polar wander on Enceladus.	X		
		O3: Characterize the chemistry of the Enceladus plumes.	**I1:** Determine the composition of the plume, including isotopic abundances.	X		
		O4: Understand the formation of the active region near the south pole, and whether liquid water exists beneath the area.	**I1:** Characterize the global and regional geomorphology of Enceladus' surface.	X		
			I2: Determine whether thermal anomalies exist underneath the surface.	X		
			I3: Determine the origin of the surface organic materials and its connection with interior reservoirs.	X		
		O5: Identify and characterize candidate sites on Enceladus for future *in situ* exploration.	**I1:** Determine whether extrusion of water ice or liquid water has occurred recently.	X		
			I2: Determine whether areas of extremely thin crust or exposed liquid within cracks exist.	X		

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4,
X = Primary, **x** = Secondary

Table 2.6-4. *Traceability matrix for the geosaucer.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS	PLANNING MEASUREMENT APPROACH	PLAN INSTR	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O6:** Characterize the major processes transforming the surface throughout time.	**I3:** Determine the internal magnetic signal	**M2:** Measure vector field with <0.1nT precision on the surface	**A1:** Three magnetic sensors record the magnetic field at the surface	GEO-PACK	Time series of magnetic field	Continuous magnetic field data combined with magnetic field measurements from the orbiter and montgolfière. Best if measurements are acquired simultaneously but not a very strong requirement. >1/2 Titan = 8 Earth days: may resolve field fluctuations on time scale of Saturn rotation >10 Titan days = 6 Earth months: may resolve field fluctuations on Titan orbit time scale
		I6: Characterize the dynamics off the crust	**M1:** Detection of shallow quakes	**A1:** Three seismic sensor which will provide the direction of the quake. (S-P) method for the distance	GEO-PACK	Times series of mass displacement	2 Titan days = 32 Earth days: low S/N
				A2: Displacement of the surface recorded by the beacon	GEO-PACK	Time series of Doppler-shift measurements	2 Titan days
			M2: Deformation of the surface due to tidal forces	**A2:** Displacement of the surface recorded by the beacon	GEO-PACK	Time series of Doppler-shift measurements	1–2 Titan days

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is taken from Table 2.3-1, *Science traceability matrix: orbiter,* Table 2.3-2, *Science traceability matrix: lake lander, and* Table 2.3-3, *Science traceability matrix: montgolfière.*

Table 2.6-4. Traceability matrix for the geosaucer, cont'd.

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS	PLANNING MEASUREMENT APPROACH	PLAN INSTR	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O7:** Determine the existence of a subsurface liquid water ocean.	**I2:** Determine if the crust is decoupled from the interior and the thickness and rigidity of the icy crust.	**M4:** deformation of the crust during Titan eccentric orbit around Saturn	**A1:** Displacement of the surface recorded by the beacon. The amplitude of the deformation and its phase lag provide information on the presence of a liquid layer.	GEO-PACK	Time series of Doppler-shift measurements	1–2 Titan days
		I3: Determine the induced magnetic field signatures in order to confirm subsurface liquid and place constraints on the conductivity and depth of the liquid	**M2:** Measure vector field with <0.1nT precision on the surface	**A2:** Three magnetic sensors record the magnetic field at the surface	GEO-PACK	2 Titan days = 32 Earth days: low S/N, large thermal quakes unlikely because of almost constant surface temp on Titan	By measuring the magnetic field at the surface, in the troposphere and in orbit, the induced signal of an Europa-like ocean could be detected.
		I4: Characterize the depth of the icy crust and the nature of the underlying layer.	**M1:** Record the seismic waves reflected at the base of the icy crust	**A1:** Three seismic sensors will record the waves produced by tidal or telluric events. The time between the direct wave and the reflective waves will provide the information on the depth of the icy crust and the nature of the underlying layer	GEO-PACK	Times series of mass displacement	2 Titan days

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is taken from **Table 2.3-1**, *Science traceability matrix: orbiter,* **Table 2.3-2**, *Science traceability matrix: lake lander, and* **Table 2.3-3**, *Science traceability matrix: montgolfière.*

Table 2.6-4. *Traceability matrix for the geosaucer, cont'd.*

MISSION GOALS	SCIENCE OBJECTIVES	SCIENCE INVESTIGATIONS	REQUIRED MEASUREMENTS	PLANNING MEASUREMENT APPROACH	PLAN INSTR	DATA PRODUCTS	MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O8:** Determine the state of internal differentiation, whether Titan has a metal core and an intrinsic magnetic field, and constrain the crustal expression of thermal evolution of Titan's interior.	**I2:** Determine whether Titan has a dynamo	**M2:** Measure vector field with <0.1nT precision on the surface	**A1:** Three magnetic sensors record the magnetic field at the surface	GEO-PACK	Time series of magnetic field	Continuous magnetic field data combined with magnetic field measurements from the orbiter and montgolfière.
		I3: Characterize Titan's internal structure	**M1:** Detect the waves that travel through Titan's interior	**A1:** Three seismic sensor, which will record the waves that travel through Titan-s interior. Quakes generated by tides or telluric activity will provide the signal	GEO-PACK	Times series of mass displacement	2 Titan days
			M2: Motion of the surface— the presence of a liquid iron core partially controls the amplitude and phase lag of the surface displacement.	**A2:** Displacement of the surface recorded by the beacon	GEO-PACK	Time series of Doppler-shift measurements	2 Titan days

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; A1…A4 = Approach 1…Approach 4; M1…M4 = Measurement 1…Measurement 4

NOTE: The numbering of each objective, investigation, approach, and measurement is taken from **Table 2.3-1**, *Science traceability matrix: orbiter,* **Table 2.3-2**, *Science traceability matrix: lake lander, and* **Table 2.3-3**, *Science traceability matrix: montgolfière.*

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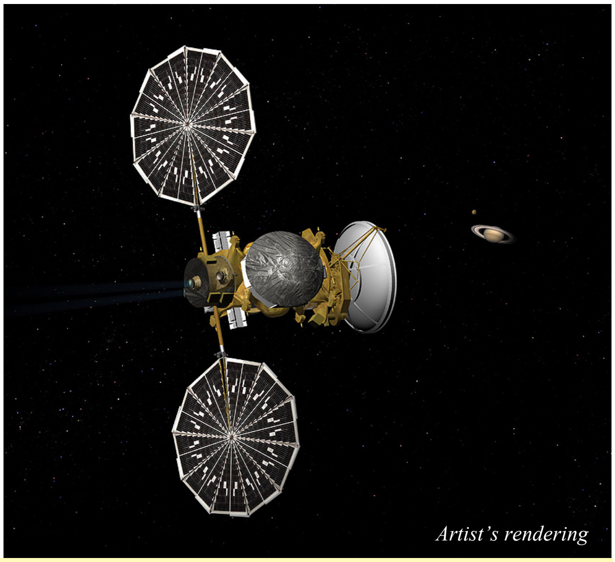
3.0 MISSION ARCHITECTURE ASSESSMENT



The TSSM Study Team has identified architectures from a rich set of potential missions that yield the best science return for mission cost, and provide a surprisingly flexible project options structure that maximizes the likelihood of mission success. The chosen Baseline mission architecture and its chain of options meet or exceed all requirements of the study's charter.

3.1 Introduction and Study Context

Since NASA began studies of potential outer planet Flagship missions in fiscal 2007, the study teams examining Titan-related missions have operated under three versions of a study charter. The charter for phase 1 of the studies, the Titan Explorer (TE07) Study, remained unaltered throughout that study phase. Phase 2 began in February 2008 with the current Titan Saturn System Mission Study and a new charter, here dubbed the "Initial Charter." That charter made several changes to the TE07 charter, including introduction of explicit international participation (see Appendix G for a description of the context for international participation in this study), addition of Saturn system and Enceladus as Level 1 science, and a hard cost cap at \$2.1B (FY07). Work was started under the Initial Charter and initial results were reported at the NASA Interim Review in June 2008. On June 20, 2008, the study team was given a new charter, here dubbed the "Revised Charter," with additional updates that changed the study's direction. Results of work performed under the Initial Charter, such as description of a flight system and mission concept that meets a hard \$2.1B (FY07) cost cap, remain useful under the Revised Charter and are reported here.

Table 3.1-1. Summary of changes in the studies' charters.

	TE07	Initial Charter Feb 2008	Revised Charter June 2008
Maximum Cost to NASA (\$FY07)	~\$3B, soft	\$2.1B, firm	<\$3B, soft
Platforms available for science	All (orbiter, lander, montgolfière, etc.)	NASA orbiter, optional ESA *in situ* elements	NASA orbiter, ESA *in situ* elements
Science scope	Titan	Titan + Saturn system (including Enceladus)	Titan + Saturn system (including Enceladus)
Launch Date(s)	2016–2017	2016–2017	2020 (assess 2018–2022)
RPS types allowed	MMRTG, ASRG	MMRTG	MMRTG, ASRG
DSN capabilities	"70 m equivalent" stations at Ka-band	Current 34 m stations	Current 34 m stations
New Technologies	No specific limit	Limit one "significant new technology"	Conservative approach—no limit specified
Aerocapture	Allowed	Not allowed	Not allowed

3.1.1 Constraints from the Study Charters

Table 3.1-1 summarizes the evolution of NASA-specified mission constraints and parameters from the TE07 study through the current study. Items not described in that table are unchanged from the TE07 study.

Launch Services and Associated Costs

Shown in Table 3.1-2, the study Ground Rules provided a list of launch vehicles to consider as well as a \$FY07 cost to use in the study for each vehicle. Real year costs were estimated to compare architecture options. The table also shows the launch mass to a C_3 of 15 km^2/s^2, which is representative for a chemical-propulsion gravity-assist trajectory to Saturn.

Table 3.1-2. Launch vehicle costs.

Vehicle	Cost ($FY07)	Cost ($RY)	Mass to C_3 of 15 km^2/s^2 (kg)
Atlas V (401)	$125M	$186M	2565
Atlas V (501)	$130M	$194M	1910
Atlas V (511)	$140M	$204M	2810
Atlas V (521)	$150M	$224M	3415
Atlas V (531)	$160M	$239M	3960
Atlas V (541)	$170M	$253M	4460
Atlas V (551)	$180M	$268M	4845
Delta IV (4050H-19)	$475M	$708M	7105
Ares V	$475M	$708M	39,951

3.2 Architecture Selection

This study follows a lengthy series of studies, dating back to 1998 for studies involving Titan orbiters, and to 1996 for Titan aerial vehicles (see Appendix F, *Previous Mission Studies*). Based on those studies, especially those conducted in 2002 or later, it was clear that designing a scientifically justifiable Titan orbiter mission within the resource constraints of this study's initial ground rules would not be an easy task. The team is delighted to have found an architecture and design that appears to fit within those constraints. In response to the Revised Charter, the team has found a "sweet spot" architecture and design that provides significantly increased science return for a modest increase in cost to NASA. This is adopted as the TSSM Baseline mission concept. Both the Baseline mission concept and a NASA-only mission concept (derived from the Baseline) feature a suite of realistic descope options that provide for a robust implementation plan that captures Level 1 science requirements.

3.2.1 Selection Process and Criteria

With a wealth of previous studies to draw upon it was not necessary to invent a new process for defining and selecting candidate architectures. In particular the process used for the "$1B Box" (Reh 2007) studies laid the groundwork for combining a survey of possible architectures, further study of likely candidates, and relative performance assessments, to populate the selection space. That study also provided rough estimates of the costs of various components of missions to the Saturn system (flight system elements, operations, science, etc.), so architectures that were far outside of resource constraints could be quickly identified and eliminated. Results of the TE07 study served this same purpose for a narrower range of architectures.

Architecture selection occurred in two separate "passes" through the selection process, distinguished by differences in selection criteria between the two versions of the Study Charter, and separated in time.

The first step was a survey of possible architectures. **Figure 3.2-1** illustrates the architecture trades tree for this process. Since the architecture at Titan was fairly narrowly speci-

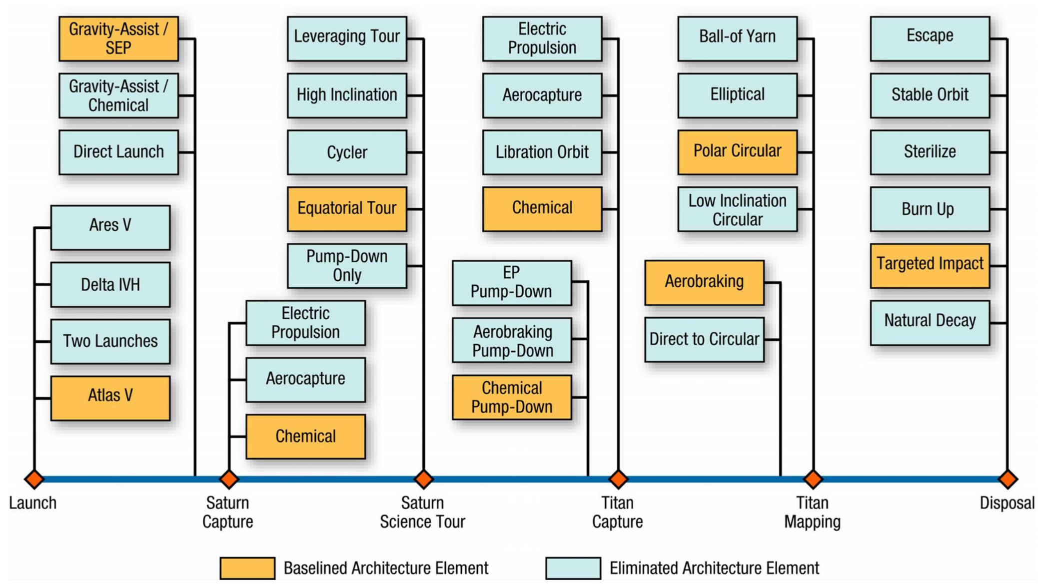


Figure 3.2-1. Architectural trade tree.

fied the principal architectural issues involved delivery, from Earth to the Saturn system and from Saturn arrival to Titan orbit, and made the architectural survey a mission-design-intensive effort. This led to a set of architectures based on single launches on the available launch vehicles, or launches on separate launch vehicles, followed by combinations of inner solar system gravity assists and/or Solar Electric Propulsion (SEP) to reach Saturn. Once at Saturn the choices were to use a chemical-propulsive plus gravity-assist tour and pumpdown, or to include Radioisotope Electric Propulsion (REP) in the pumpdown. Options for delivery timing of the *in situ* elements are not truly architectural, since they do not affect which fundamental elements are used, so they were not included in the architectural decisions. This architecture survey was sufficiently broad that upon adoption of the revised Study charter no new general survey was necessary. The suite of options developed for the first pass was sufficient for the second pass also.

The next step was to assess the science accommodation potential and mission resource requirements of the candidate architectures. The study JSDT, with considerable heritage from previous studies and the SSE Decadal Survey, drafted a set of science objectives, then derived investigations and a "planning payload" to address those objectives. Science accommodation potential was judged on the ability of a mission concept (including a strawman operations concept) to accommodate that planning payload and perform the science investigations, and to carry further resources for accommodation of the ESA *in situ* elements. Mission resource requirements include such aspects as total mission cost, total cost to NASA, schedule, DSN equipment requirements and loading, etc.

In the final step of the first pass, the most attractive candidate architectures (per the Initial Study Charter metrics) received further analysis, leading to selection of a cost-capped mission architecture. For analyses under the Initial Study Charter, *total cost to NASA was the overriding factor for selecting that mission architecture*. The initial study ground rules specified that the cost to NASA must be less than or equal to the $2.1B cap, with science as the "free parameter." Trades of trip time vs. delivered mass were examined, including both chemical and SEP trajectories, with attention paid to those with the lowest anticipated costs. Based on experience the team chose to analyze in depth an architecture that was thought to be the least costly, in part because it is the simplest. That assessment appears to be borne out by the analyses, and that architecture was selected for the cost-capped mission architecture and design.

Subsequent analysis revealed that this architecture and design most likely would fit the $2.1B cost cap only for a NASA-only mission (i.e., with no ESA *in situ* elements). Such a mission concept meets all the requirements of the Initial Study Charter and Ground Rules, but offers few options for descope and thus is not a good candidate for a Baseline mission. But it does qualify for a NASA-only Floor mission, and was adopted as such under the Revised Study Charter.

After adoption of the Revised Study Charter, some of the architectures analyzed in the first pass were re-analyzed with the addition of SEP options, deemed too costly for the hard cost cap of the first pass but available under the relaxed constraints of the second pass. This led to selection of a Baseline mission architecture with greater capability and robustness to deliver ESA *in situ* elements. Unlike the first pass, the second focused on those that, relative to the NASA-only Floor architecture selected in the first pass, provided the greatest increase in science return per increase in total mission cost: "sweet spot" missions. The team identified a SEP-based architecture that yields significantly greater science return for a modest increase in total mission cost. This is adopted as the Baseline architecture.

Table 3.2-1 shows various architecture options and their cost delta compared to the Baseline (Case 3). The cost delta is an estimate based on launch vehicle cost, a fully burdened cost of $145M RY for a SEP stage and an average burdened cost of $44M/yr RY for interplanetary operations. The "*In situ* element" column denotes whether an option carries a balloon and lander (B+L) or no *in situ* elements.

Although the TSSM mission has been shown to be feasible without SEP, several considerations contributed to the decision to

Table 3.2-1. *TSSM Baseline options.*

Case	Launch Vehicle	Cruise Propulsion	FT to Saturn (years)	*In Situ* Element	($RY)	($FY07)
1	A541	Chemical	8	none	($377)	($273)
2	A551	Chemical	10.5	B+L	($205)	($145)
3	A551	SEP	9	B+L	---	---
4	A521	SEP	7.5	none	($223)	($160)
5	Delta IVH	Chemical	9	B+L	$244	$148
6	Delta IVH	SEP	6	B+L	$299	$215
7	Ares V	Chemical	3	B+L	$159	$136

include SEP in the Baseline mission for the Earth-to-Saturn transfer. Out of these considerations, one stood out: robustness against mass growth that would require a larger launch vehicle. At 10.5 years trip time the Atlas V 551 Chemical with *in situ* option (**Table 3.2-1**, Option 2) has nearly exhausted all capacity-increasing options, limiting its ability to accommodate mass growth beyond the 33% mass margin. Further mass growth would require a larger launch vehicle. Since the Chemical option already uses the largest of the Atlas V series, that larger launch vehicle would have to be the Delta IV Heavy, at a cost increase of $440M RY ($295M FY07). In contrast, the Atlas V 551 SEP with in situ option chosen for the Baseline mission (**Table 3.2-1**, Option 3) still retains significant opportunities for capacity increase (for instance, via increasing trip time) and is thus far more robust against mass growth.

Other considerations are also important. The chemical option's increased trip time requires reducing the Baseline 22-month Titan orbital prime mission to 16 months to keep the mission duration within the 14-year nominal lifetime of the RPS systems. Examples of additional considerations include:

- SEP offers significantly more launch flexibility than the chemical options, with more frequent, longer-duration windows that vary little from year to year.
- Developing the SEP stage offers significant feed-forward benefits to future missions.

The convergence of all these considerations led the team to adopt the SEP option for the Baseline mission.

3.2.2 Results and Summary

The TSSM Study Team successfully identified mission architectures that fully satisfy all the requirements of the Revised Charter and its ground rules. Those architectures are described in this section.

The second pass through the architecture selection process outlined above converged on a Single Atlas Launch with SEP option, described in §3.3.1 and shown in **Foldout 1** (**FO-1**) of §4.3, as the TSSM Baseline. This option provides the largest increase in science return over the NASA-only Floor option, at a minimal accommodation cost to NASA. ESA provides the *in situ* elements. This mission concept provides descope options for both NASA and ESA to a scientifically attractive NASA/ESA Floor mission, yielding a very robust project implementation approach (see §3.3.1.2).

The first pass through the architecture selection process identified a NASA-only option that is the Single Atlas Launch, described in §3.3.2.2 below. Subsequent analyses in the second pass revealed SEP as an attractive element for that architecture, and it was adopted. Transition to this option from the Baseline mission can only occur if ESA decides not to participate in the mission. Transition to a viable NASA-only mission can occur at any point in any descope sequence from the Baseline mission to the NASA/ESA Floor mission, and at any time. The full NASA-only mission has a number of descope options available between PDR and CDR, and some after CDR (see §3.3.1.2).

3.3 Architectural Options

This section describes the architecture space examined, yielding the current Baseline architecture and NASA-only architecture that best fit the study's ground rules, as well as multiple alternate architectures that provide various enhancements. It begins with an assessment of trajectory and launch vehicle options and moves to descriptions of the Baseline architecture, NASA-only architecture, and alternate architectures; in many instances architectures are compared to the Cassini-Huygens mission. For completeness it finishes with a brief discussion of architectures noted but not analyzed.

3.3.1 Baseline Architecture Description

3.3.1.1 Single Atlas Launch, With SEP and ESA-Contributed *In Situ* Elements

The TSSM Study's Baseline Architecture is the architecture that best aligned with the Revised Ground Rules. This concept's flight system delivers and supports an allocation of 830 kg of ESA-contributed *in situ* elements with a single launch on an Atlas V 551 launch vehicle, with a SEP stage to augment the launch vehicle. There are multiple Earth-to-Saturn transfer options available as prime and backup trajectories from 2018 through 2022. The best pairing of these is an EVEE-SEP trajectory launching in September 2020 and arriving at Saturn in October 2029, delivering up to 5755 kg to Saturn approach, and an EVEE-SEP backup trajectory launching in 2022 for a 2031 arrival, delivering up to 5625 kg to Saturn approach with a smaller SOI burn. Transfer times to Saturn are greater than for the Cassini-Huygens mission because in the 2018–2022 launch period Jupiter gravity assists to Saturn are not available (Jupiter gravity-assists would be available in 2015–2017 and 2034–2036). **FO-1** in §4.3 shows a timeline for the Baseline mission.

With either prime or backup trajectories, the NASA orbiter releases the ESA *in situ* elements on approach to Titan flybys after its Saturn Orbit Insertion (SOI) maneuver. Their entries into Titan's atmosphere are separated in time to avoid simultaneous critical events. During and after their entries the NASA orbiter provides data relay to Earth for the *in situ* elements.

Orbiter science observations begin in Saturn orbit, immediately after SOI. That SOI initiates a two-year pumpdown (with respect to Titan) and Saturn system science tour that includes seven close flybys of Enceladus, including sampling of the south polar plume. During this time the orbiter also functions as a data relay for the *in situ* elements' prime missions, with particularly high data relay rates possible during the tour's many close Titan flybys. Upon completion of the tour the orbiter performs a Titan Orbit Insertion (TOI) maneuver, placing the orbiter into an 720 × 15,000 km initial orbit that saves ~240 m/s of ΔV (with respect to inserting directly into a circular mapping orbit at 1500 km altitude) and sets up science observations that cannot be done from the circular mapping orbit. From that orbit, periapse reduction initiates ~2 months of aerosampling/aerobraking passes for science and for orbit circularization toward the mapping orbit. When aerobraking has reduced apoapse to 1500 km altitude a periapse-raise maneuver circularizes the orbit at 1500 km for the mission's 20-month prime Circular Orbit Phase. During orbital operations at Titan the orbiter can provide high-rate data relay for any potential extended missions of the *in situ* elements. The TSSM trajectory design leaves options open for an orbiter extended mission.

The mission total post-launch ΔV for this concept is 5127 m/s (2377 m/s chemical and 2750 m/s SEP). Section 4.3.10 covers mission ΔV in detail.

In many respects comparison of the TSSM Baseline orbiter to the Cassini spacecraft is appropriate, since the two spacecraft perform many of the same functions in the same environment. Like the Cassini spacecraft, a large propulsion system and a 4 m HGA dominate the appearance of the TSSM Baseline orbiter, echoing the most challenging aspects of the TSSM mission design: placing the spacecraft where it needs to be to make its science observations, and sending the data to Earth, commensurate with the realities of current RPS program capabilities and limitations. Unlike the Cassini Saturn orbiter, the TSSM orbiter's primary mission is in orbit around Titan, so the Earth-spacecraft-primary geometry changes on an hourly basis, not a daily or weekly basis. The need to decouple pointing of the science

instruments from pointing of the HGA drives the main difference between the Cassini and TSSM orbiters, gimbaling of the TSSM HGA where Cassini's is body-fixed. Aerobraking is another difference, but the relatively low heating rates and forces expected during TSSM's Aerobraking Phase make this a minor driver. Orbiting rather than flying by Titan, and the focused optimization of TSSM's payload for its specific tasks at Titan, are the main reasons that TSSM's science capability at Titan far surpasses Cassini's.

The TSSM concept presents no unprecedented operational issues to the orbiter. Launch and transfer to the outer solar system follow in the footsteps of Galileo and Cassini. In many aspects the Titan-orbiting phases of the TSSM concept are reminiscent of recent Mars high-resolution mapping missions, including aerobraking and operating a gimbaled HGA. Delivery of the *in situ* elements to Titan is very much akin to the delivery of the Huygens Probe by the Cassini Orbiter. SOI and the Saturn system tour are very Cassini-like. Even communicating with a fixed Titan lander compares with relay of MER data and commands by Mars-orbiting assets. The novel operations concept is communicating from an orbiter with a very mobile Titan montgolfière, but even that is not expected to be a significant challenge due to the low-speed nature of Titan's winds at the altitudes to be flown. Strategy and schedules of orbiter communications with Earth should be similar to those of Mars orbital missions, but using Ka-band instead of X-band. Planetary Protection requirements allow a simple, natural orbital decay and entry for spacecraft disposal.

3.3.1.2 Architecture Implications for Project Options Structure

Part of the attractiveness of the Baseline mission option described above is that it carries with it a robust and very flexible set of options for mission rescope before PDR and descope after PDR. **Figure 3.3-1** illustrates the structure of this option space.

The graph's vertical axis represents notional relative science value, as judged by the TSSM JSDT. At the top is the gray "plank" representing the Baseline mission, with its full complement of ESA *in situ* elements, orbiter accommodation, best mission design (including

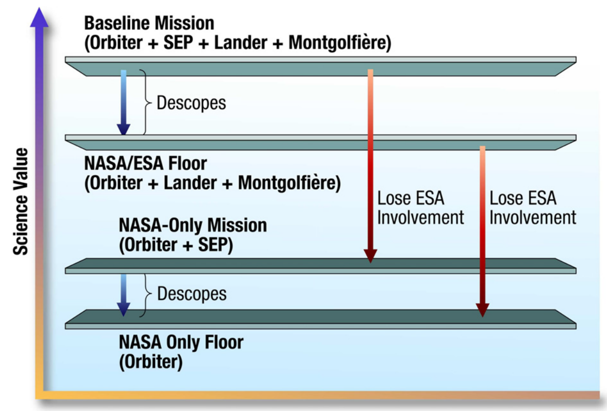


Figure 3.3-1. *NASA/ESA and NASA-only mission architectures include robust descopes while remaining above the science floor.*

SEP), and prime mission duration. Beneath that, to the left, is an arrow representing the change as various descope options of widely varying fiscal impact are implemented. NASA and ESA both have options along that track, with much flexibility in which options are exercised and when (see §4.11.7.8). Ultimately, for a NASA/ESA mission, it arrives at the lower gray plank, the NASA/ESA Floor, whose flight elements are an orbiter without SEP and the ESA *in situ* elements. This is considered a "Floor" because it is the lowest level at which the NASA orbiter can deliver the ESA *in situ* elements while retaining its own minimum science return.

If ESA decides not to participate in TSSM it becomes a NASA-only mission, represented by the lowest two green planks. The upper of the two represents an orbiter mission with all the orbiter science capability of the Baseline mission, with SEP. Exercising all of a set of descope options, mostly identical to the NASA-side descope options of the NASA/ESA mission, arrives at the lowest plank, the NASA-only Floor, a reduced-capability, chemical-propulsion-only orbiter that still meets the mission science floor.

Red arrows to the right on the graph represent transitions from a NASA/ESA mission to a NASA-only mission. If that decision were made before any orbiter descopes were exercised, then the resulting NASA-only mission is the upper of the two NASA-only mission planks, with the full set of orbiter descope options intact. Transition after orbiter descopes

***Table 3.3-1.** Summary characteristics of the Baseline architecture and alternates.*

	Baseline	NASA / ESA Floor	NASA-only	NASA-only Floor
Flight Elements	NASA orbiter and SEP stage, ESA montgolfière and lander	NASA orbiter, ESA montgolfière and lander	NASA orbiter; SEP stage	NASA orbiter only
Launch Vehicle	Atlas V 551	Atlas V 551	Atlas V 551	Atlas V 551
Launch Date	2020	2020	2020	2020
Backup Launch Date	2022	2022	2022	2022
Transfer Trajectory	SEP/EVEE, 9 yrs	VEE or other gravity assist, 10.5 yrs	SEP/EVEE, 9 yrs	VEE or other grav assist, 10.5 yrs
SOI & Initial Orbit	Chemical; 214-day period	Chemical; 214-day period	Chemical; 214-day period	Chemical; 214-day period
ESA *in situ* element release timing	Montgolfière: 1st Titan flyby; Lander: 2nd Titan flyby	Montgolfière: 1st Titan flyby; Lander: 2nd Titan flyby	NA	NA
Saturn System Tour Duration	2 years	2 years	2 years	2 years
Enceladus Flybys During Tour	7 or more	7 or more	7 or more	7 or more
Titan Flybys During Tour	16	16	16	16
Data Relay for *in situ* elements	During Saturn tour	During Saturn tour	NA	NA
TOI & Initial Orbit	Chemical; 720 × 15,000 km	Chemical; 720 × 15,000 km	Chemical; 720 × 15,000 km	Chemical; 720 × 15,000 km
Aerobraking/ Aerosampling Duration	2 months	2 months	2 months	2 months
Mapping Science Mission Duration	20 months	16 months	20 months	16 months
Extended Orbital Mission Possible?	Yes	Yes	Yes	Yes
Option for high-rate relay for *in situ* element extended mission?	Yes	Yes	NA	NA
Spacecraft Disposal	Naturally assisted, targeted burnup/breakup into Titan atmosphere	Naturally assisted, targeted burnup/breakup into Titan atmosphere	Naturally assisted, targeted burnup/breakup into Titan atmosphere	Naturally assisted, targeted burnup/breakup into Titan atmosphere

are exercised goes to a NASA-only mission at a lower level than the uppermost plank. The limiting case is transition after all available orbiter descopes of the Baseline mission are implemented, which goes directly to the NASA-only Floor mission. An important characteristic of this structure is that regardless of when an ESA decision not to participate might be made, even up to the launch pad, there are clear transition pathways from the NASA/ESA mission to a viable NASA-only mission.

If an ESA decision not to participate were made early, during pre-Phase A or Phase A, at its discretion NASA could use the extra resources to re-optimize the mission. Examples of such options would be moving to a smaller launch vehicle, conducting a more exhaustive science campaign by adding capabilities to the current instrument suite or adding propellant, or even addition of a NASA or other internationally contributed *in situ* element.

Table 3.3-1 summarizes important aspects of the four missions represented in **Figure 3.3-1**. All four are scientifically exciting missions. The robustness of the NASA orbiter science investigation is evident from the consistency across the options of the aspects that influence orbiter science.

TSSM's Baseline mission architecture provides this rich, flexible Project Options structure that yields a robust project implementation plan. NASA and the TSSM Project Manager would have great flexibility in dealing with problems as they arose.

3.3.2 Alternate Architectures

3.3.2.1 Single Atlas Launch, with ESA-Contributed *In Situ* Elements

This architecture is similar to the Baseline architecture described in §3.3.1.1, except that it lacks a SEP stage. Aside from the SEP stage, it differs from the Baseline architecture mostly in that it uses a different and longer-duration gravity assist tour in the inner solar system. The NASA orbiter's science mission and delivery of the ESA *in situ* elements are essentially unchanged from the Baseline. This architecture was chosen as the basis for the NASA/ESA Floor mission shown in **Figure 3.3-1**.

3.3.2.2 Single Atlas Launch, NASA-only

This architecture is similar to that described in §3.3.1.1 except that it carries no ESA *in situ* elements, the case should ESA decide not to participate in the mission. It retains the SEP stage and its NASA orbiter is identical to the Baseline NASA orbiter. Mass formerly allocated to the ESA elements would become unallocated mass. If an ESA decision not to participate were made early enough, NASA would have that mass to use at its discretion. This architecture is the basis for the NASA-only mission shown in **Figure 3.3-1**.

3.3.2.3 Delta IV Heavy Launch

A Delta IV Heavy launch vehicle is significantly more capable than the Atlas V 551, so for the same trajectory it can loft greater mass, and for the same mass it can achieve a higher C_3 and thus potentially use a shorter-duration transfer orbit. The difference is sufficient that TSSM could use it to achieve some of both, reducing the transfer time by ~1.5 years and adding sufficient orbiter propellant to carry the ESA *in situ* elements into Saturn orbit and through most of the pumpdown. This would allow timing the last half of an aerial *in situ* element's prime mission to overlap with the NASA orbiter's time in Titan orbit, greatly increasing the potential data return from the *in situ* element's prime mission. This advantage comes at a disproportionately greater total mission cost, since the Delta IV Heavy costs nearly $300M more than the Atlas V 551.

3.3.2.4 Two Launches

This architecture has the NASA orbiter launch on one launch vehicle, and the ESA *in situ* elements on another. It has multiple distinct advantages and multiple distinct disadvantages.

The advantages include greater total delivered mass (especially increasing the total delivered mass of the *in situ* element), resolution of potential NASA/ESA schedule mismatch (see Appendix G), delivery of the *in situ* elements with the NASA orbiter already in orbit, and greater opportunity for Cassini-Huygens-like collaboration across flight element boundaries. With this architecture, the NASA part is very much like the NASA-only Single Atlas Launch Architecture described in §3.3.2.2, with its advantages for the orbiter. The *in situ* elements would launch on another vehicle, but the current policies on launch of nuclear materials restrict the launch vehicle options available. If the *in situ* elements use one or more RPSs, under current policies they would have to launch on a US launch vehicle from a US launch facility. That vehicle probably would be a smaller Atlas V than used for the NASA element, but even with an Atlas V 401 the delivered *in situ* element mass could be greater than that of the Baseline mission. With two separate launches, the NASA element could launch two years before the ESA elements, decoupling any potential schedule mismatch between NASA and ESA programs. That schedule offset has the great advantage that it allows the NASA orbiter to finish its Saturn system science, arrive in Titan orbit, and complete much of its mapping mission before the *in situ* elements arrive. This timing has the orbiter in Titan orbit for the *in situ* elements' entire prime missions, greatly augmenting the total mission data volume from the *in situ* elements, and it allows the orbiter's mapping data to be used for informed decisions about delivery locations for the *in situ* elements. Finally, with more hardware being contributed across the Atlantic, there are greater opportunities to offset the costs of contributions with scientific participation in each other's mission elements, and possibly with other aspects of flying a Flagship outer solar system mission. These are substantial advantages that contribute to a science return potentially richer than that of the Baseline architecture.

The advantages do not come without costs, which are the primary disadvantages. The

launch services and launch approval, if contributed by the US, adds to the total cost to NASA, on top of the cost of the NASA-only Single Atlas Launch mission. With this architecture ESA must develop and build another flight element, a cruise stage to deliver the *in situ* elements to Titan.

3.3.2.5 Aerocapture at Titan

Although the current study's ground rules exclude the use of aerocapture, that technique remains an attractive option due to its delivered mass advantages. The TE07 Study focused on the aerocapture option and analyzed it in detail (see that study's Final Report). It would not impact the ability to address that study's primary science objectives, which were limited to Titan. But it would indeed impact some of TSSM's science objectives, since aerocapture at Titan would rule out a pre-Titan-orbit Saturn system tour, and thus rule out addressing Saturn system and Enceladus science objectives beyond the very limited observations that could be accomplished from Titan orbit.

3.3.3 Architecture Options Not Analyzed

3.3.3.1 Ares V Launch Vehicle

The Ares V launch vehicle is currently under design for the task of sending crewed spacecraft to the Moon, a task handled four decades ago by the Saturn V. With a similar launch capacity to a C_3 near zero (nearly 50,000 kg, compared to the Delta IV-Hs ~10,000 kg), it is expected that the Ares V could greatly expand the envelope of feasible science missions within the solar system (Reh et. al. 2008). Applied to TSSM, it is likely that an unmodified Ares V could launch the NASA orbiter and the full retinue of ESA *in situ* elements together directly from Earth to Saturn; supplied with an appropriate Centaur-like upper stage, it might send twice that mass on the direct-to-Saturn trajectory. But current NASA ESMD development schedules do not have the Ares V available for 2020 SMD launches. Like the Delta IV-H, the Ares V advantages come at a disproportionately greater total mission cost.

3.3.3.2 Radioisotope Electric Propulsion

Radioisotope Electric Propulsion (REP) has received considerable attention in recent literature as a useful technique for outer solar system exploration. But spacecraft suited for REP are very lightweight ones with efficient (i.e., low-mass), high-power RPS systems. REP systems trade thrust against I_{sp}, and the proportionality constant in the trade is a direct function of the electric power available. For I_{sp} that makes REP attractive, the mass of the TSSM flight system and the relatively low-power MMRTG system yield accelerations far too small to be useful in a reasonable pumpdown tour duration.

3.3.3.3 Hyperbolic Aerobraking

Although aerobraking is typically done while in orbit around the target body, it is possible to do aerobraking passes during hyperbolic flybys. The Cassini spacecraft has done a mild version of this in its close flybys of Titan, although for Cassini the atmospheric drag effects were small and not a desired product of the flybys. But atmospheric drag can indeed decrease slightly the magnitude of V_∞, and thus over time decrease the ΔV needed for orbit insertion. Titan's atmospheric variability requires that the ΔV from such be kept small, so encountering denser-than-expected atmosphere would not cause excessive thermal loading. This yields a long pump-down duration unless assisted by propulsion. Also, uncertainty in the departure velocity of each flyby must be cancelled via propulsion to ensure a return to Titan, so at Titan the technique does not save significant propellant mass.

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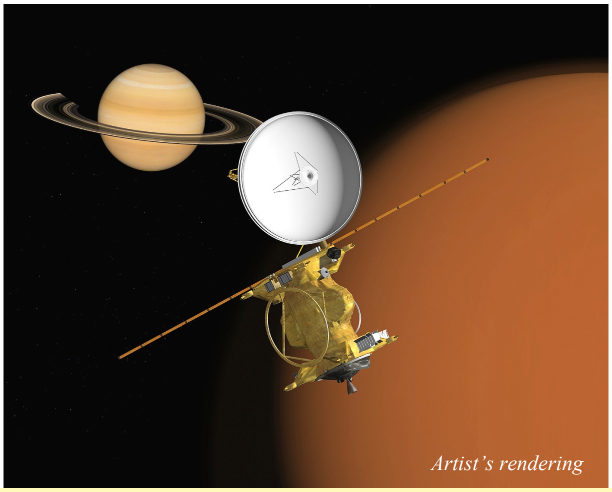
4.0 MISSION CONCEPT IMPLEMENTATION



The fascinating worlds revealed by the Cassini-Huygens mission have stimulated great interest in the science community. Several studies over the last decade have looked at Titan as a world tailor-made for application of techniques that would allow enhanced exploration. Building on these past studies as well as lessons learned from numerous recent deep space missions, the implementation developed for TSSM has resulted in a flight and mission system that is inherently low in risk and cost, yet capable of revolutionary science return.

4.1 Mission Architecture Overview

The Titan Saturn System Mission (TSSM) Baseline mission derives from a careful consideration of alternative architectures as discussed in §3.0. The Baseline mission consists primarily of a Titan orbiter augmented with a solar electric propulsion (SEP) stage, capable of meeting all Level 1 science requirements, including Saturn system science as well as targeted science at Enceladus during an extended Saturn Tour Phase. The Baseline mission would also accommodate two ESA-provided *in situ* elements, a long-lived montgolfière aerial vehicle that would circumnavigate the moon at a nominal altitude of 10 km and a battery powered lander targeted at Titan's northern lakes. These elements would be delivered to Titan by the orbiter spacecraft and supported during their science mission with two-way data relay through the orbiter telecom assets. The TSSM mission architecture represents a robust and scientifically rich implementation that would produce a giant leap in our understanding of Titan, the once and future Earth.

4.1.1 Draft Level 1 Requirements (Science Only)

Level 1 requirements are negotiated between the NASA program office and the project after careful assessment of risk, allocated resources, and in consultation with JPL management, science representatives, and key project staff. Preliminary Level 1 requirements are required at the end of Phase A with the final version approved by the end of Phase B.

Level 1 requirements levied on this study by the Statement of Work include two that directly pertain to science:

- The study is directed to investigate and propose an architecture consisting of a Titan orbiter that does not utilize aerocapture. The orbiter shall have the capability of delivering and supporting a Titan *in situ* vehicle(s) that is furnished by ESA as part of the collaborative program.
- Include Saturn system science as a Level 1 requirement, including Enceladus science.

These broad requirements, along with the guiding documents referenced in §2.0, were taken by the TSSM JSDT as the basis from which a full set of science goals, objectives, investigations and mission requirements were derived, as detailed in the science traceability matrix in §2.0. This matrix is the basis of the TSSM design and will continue to serve as the basis for the generation of preliminary Level 1 science requirements in Phase A.

4.1.2 Key Driving Requirements

A number of programmatic constraints were placed on this study, posing driving requirements on the design of the Titan Saturn System Mission and Flight System. These include the elimination of aerocapture as an available technique for Titan orbit insertion, and elimination of the use of DSN 70 m stations as an option for science data downlink (with the exception of critical-event coverage and safe mode). In addition, science requirements were expanded, directing that the mission perform Saturn system and Enceladus science as a Level 1 requirement, and that accommodation be provided for *in situ* elements that would be supplied by ESA.

The elimination of aerocapture highlights perhaps the most significant driving require-

ment that differs from previous Titan mission studies. Propulsive capture at Saturn and at Titan brings with it the requirement for a large propulsion system to provide the necessary ΔV for these maneuvers. This in turn puts extra emphasis on keeping Flight System dry mass as low as possible to enable a mission that can remain compatible with a reasonably affordable EELV while accommodating a robust *in situ* payload. This constraint has driven both Flight System and mission design to devise innovative solutions that minimize ΔV and mass to enable a robust mission concept.

The restriction on the mission to use only the 34 m DSN stations for science data downlink has emphasized the challenges presented by the very long ranges that the telecommunications system must span. Prior mission studies, as well as the current Cassini mission, have assumed use of the 70 m stations to provide up to four times the science data volume available from a 34 m station for a given pass length. This limitation has led the Flight System design to adopt a 4 m HGA operating in Ka-band to maximize data return.

The requirement to perform Saturn system and Enceladus science has been easily and effectively incorporated into the mission and, in fact, is a benefit that flows from the adoption of a propulsive capture design. Capture into Saturn orbit prior to arrival at Titan provides ample opportunity to make observations in the Saturn system, and judicious tour design has enabled multiple close flybys of Enceladus with very little impact on required fuel or mission length.

Accommodation of *in situ* elements in the mission and Flight System design has a number of impacts, both direct and indirect which are addressed in detail in Appendix I, but this capability provides a significant boost in science return that is well worth the challenges posed.

4.1.3 Baseline Mission Description

The Baseline mission concept includes an orbiter Flight System, which accommodates two *in situ* elements. The Flight System travels by means of an inner planet gravity assist trajectory and reaches Saturn approximately 9 years after launch. Augmentation of ΔV capability is provided during roughly the first half of the trajectory by a solar electric propulsion (SEP) stage, which is jettisoned about five years into the mission. Following the remainder of the cruise, the orbiter's chemical propulsion subsystem places the Flight System into orbit around Saturn followed by approximately two years of Saturn system science, including a minimum of seven Enceladus flybys, while the Flight System uses repeated satellite gravity assists and maneuvers to greatly reduce the propellant needed to insert into orbit around Titan.

The *in situ* elements delivered by the orbiter include a montgolfière aerial vehicle and a lake lander (see Appendix J). Current planning for the Baseline mission is that the montgolfière element would be released at the first Titan flyby after Saturn orbit insertion for ballistic entry into Titan. The lander element would be targeted and released at the second Titan flyby to ensure robust communications links during its primary mission.

Titan orbit insertion is accomplished at the end of the Saturn Tour Phase using the main engine. Capture into a polar elliptical Titan orbit would be followed by a two-month aerobraking and aerosampling phase, leading to a circular 1500 km orbit for the 20 month orbital science phase. Key mission parameters are shown in **Table 4.1-1**.

At an orbital altitude of approximately 1500 km the Flight System orbits Titan approximately five times in an Earth day. The science planning payload consists of six instruments in addition to radio science and is estimated at 108 kg (Current Best Estimate, CBE) with an orbital average power of 55 W (CBE). The telecom subsystem is sized to provide a minimum science data downlink from Titan orbit of approximately 5.4 Gb per Earth day, assuming two 8 hr DSN passes per day at maximum range (~10.1 AU). This capability would increase as the Earth-Saturn range decreases over the course of the mission. Science operations are structured to address the science objectives, with three observational campaigns optimized for available power and downlink.

4.1.4 Floor (NASA/ESA and NASA-only) Mission Description

Descoped mission concepts have also been developed, which would impact some aspects of the Baseline mission while not significantly

Table 4.1-1. *Baseline key mission parameters.*

Parameter	Baseline Value	Notes
Instruments		
Number of instruments	6	Radio science investigations make use of existing telecom hardware
Instrument mass	108 kg	Current Best Estimate. Total allocation of 165 kg including margin.
Instrument power	55 W	Current Best Estimate, orbital average during Campaign 3.
Science Accommodation		
Pointing accuracy	0.15 mrad (3 σ)	Spacecraft body pointing control accuracy during nadir-oriented non-thrusting orbital period.
Pointing stability	1.7 μrad/s (3 σ)	For body-fixed instruments in science orbit during non-thrusting periods.
Minimum duration between reaction wheel orbit desaturations	72 hours	Minimum duration between desaturation thruster firings.
Data storage	32 Gb	Science data, additional 1.75 Gb NVM available for Flight System software loads, parameter storage, and engineering telemetry and margin
Data volume capability from Titan orbit	5.4 Gb/day	Assumes 3 dB link margin, two 8 hr DSN passes per day to 34 m stations receiving whenever in view and 90% weather.
Spacecraft		
Processor speed	132 MHz	RAD750 flight computer
Available power at EOM	540 W	Power output from 4 of 5 ASRGs at EOM (defined as 13 years after launch + 3 years prelaunch storage)
Main engine thrust level	890 N	Single gimbaled 890 N HiPAT engine
Chemical ΔV requirement	2377 m/s	Includes all mission phases post SEP cruise
SEP ΔV requirement	2750 m/s	Using NEXT ion engine, 15 kW solar arrays
Total Mission Dose	<15 krad	Includes environmental and RPS dose behind 100 mils Al
Heliocentric operating range	0.7 to 9.1 AU	Minimum range defined by trajectory.

affecting mission science return. The largest of these possible mission descopes would involve elimination of the SEP stage, resulting in a somewhat longer transit time to Saturn (up to 10.5 years) while maintaining the full mass allocation for *in situ* elements. The orbiter would see very minimal changes, primarily the elimination of SEP stage interfaces. This descope, combined with the additional descopes described in §4.11.7.8, would represent what is described in §3.0 as the NASA/ESA floor.

A NASA-only mission would result from a decision by ESA not to participate. The result would be an orbiter-only mission that would still be capable of meeting Level 1 science requirements. Should the absence of ESA participation be known early enough in the development, it would be possible for NASA to consider development of a US *in situ* element(s) that could be accommodated in place of the ESA elements. Combining the loss of ESA participation with the additional descopes described in §4.11.7.8 would result in the NASA-only Floor mission.

4.2 Science Investigation

4.2.1 Planning Payload

The instruments that constitute the planning payload on the TSSM orbiter are listed in §2.4, along with a description of how the suite of instruments captures measurements to satisfy the science objectives. The purpose of the instruments described in this section is to demonstrate the feasibility of the orbiter's instrument suite and the viability of the overall mission. This is done by defining model instruments in sufficient detail to determine the resource requirements, risk, cost, and other engineering aspects of the planning payload. These definitions enable the necessary detail in the design of the spacecraft and operational scenarios.

Therefore, the instruments described in this section should be taken to be neither the final selections nor the final implementations of the orbiter instruments. Heritage and similarities with specific designs are used to demonstrate feasibility and do not imply that specific implementations are either planned or required. These instruments meet the measurement requirements while remaining within the available resources and with minimal technical and programmatic risk. These planning payload model instruments validate the measurement capability to meet the science requirements.

The payload consists of several remote sensing instruments and a set of space physics instruments. In addition, the telecommunica-

tions system provides: 1) tracking data for accurate orbit reconstruction in support of geophysical objectives; and 2) RF occultation-intensity data to support atmosphere studies. There are seven individual experiments, though other combinations of instruments may be more efficient in terms of total mass, power and cost. Individual instrument capability is not meant to pre-judge AO solicitation content or outcome.

These instruments are all within the state of the art and all have strong flight heritage. Although some instruments such as the Polymer Mass Spectrometer (PMS) have capabilities that extend the previous measurement limits, TSSM would accomplish dramatic science by putting proven, reliable instruments in orbit around Titan, not through risky technology development. The environment has no excessive features that require deviation from nominal flight hardware. The planning payload instruments, described below, demonstrate that the fully margined mass and power constraints can be met with high confidence.

The JSDT and engineering team developed a focused set of requirements and selected a planning payload based on previous studies, recent results from Cassini-Huygens, and the science requirements for the study. As a result, the planning payload is sufficient and necessary to accomplish all science measurement requirements.

4.2.1.1 Payload Accommodation: Layout and Operational Considerations

The remote sensing portion of the payload (HiRIS, TIRS, and SMS) must view in the nadir direction when in orbit about Titan. The SMS and TIRS instruments also require limb viewing and so they include pointing articulation to allow viewing the limb without off-nadir spacecraft maneuvers. As can be seen in **Figure 4.2-1**, the spacecraft provides several nadir-facing mounting locations for the remote sensing instruments, which have a conical clear field of view with at least a 30° half angle centered about the nadir direction. Nadir pointing, coupled with instrument self-articulation, is adequate to meet the science objectives, and a scan platform is not required.

The following considerations were used to place the instruments onto the spacecraft: desired viewing direction(s), required FOV, radiator requirements, spacecraft obstructions, orbit geometry, Sun and Titan positions throughout the orbit, and available mounting locations. To reduce radiation and limit external heating of the instruments, most of the instruments are placed away from the RPS units. Two instruments, TIRS and HiRIS, have 70 K–80 K detectors that are cooled with passive radiators, and their radiator FOVs are mounted so as to view in a direction away from the Sun and away from Titan at all times when in Titan orbit. The locations of several spacecraft components such as the attitude-control thrusters were optimized to enable better positioning for the instruments. Other layouts are available, but the layout shown in **Figure 4.2-1** meets the mission requirements.

The specific parameters that drove the placement of each instrument are shown below. In most cases, there are other locations where the instrument could be mounted.

- TIRS: nadir/limb view and radiator
- HiRIS: nadir view, radiator view, and avoid obstructing TIRS FOV
- SMS: nadir/limb view and avoid obstruction of HiRIS FOV
- PMS: clear view in both aerobraking and circular orbital ram directions
- TiPRA: radar dipole antenna is stretched parallel to the surface (orientation with respect to velocity does not affect measurement performance)
- Magnetometer (MAPP): avoid the HGA
- Langmuir probe (MAPP): unobstructed view of ram direction
- Plasma (MAPP): views of both ram directions and zenith
- EPS (MAPP): view of zenith

The remote sensing payload requires spacecraft pointing control shown in **Table 4.2-1**. These requirements are well within the spacecraft's pointing control accuracy of 0.15 mrad (3-sigma) and stability of 1.7 µrad/s (3-sigma), as described in §4.4.3.6. This is similar to the pointing capability required by the RF/Telecom system. This pointing is sufficient to control overlap of images and to support post-processing registration of the data.

Table 4.2-1 also shows the timing requirements for each instrument. These requirements relate to the accuracy of the time tagging of the data and to the post-processing accuracy of the

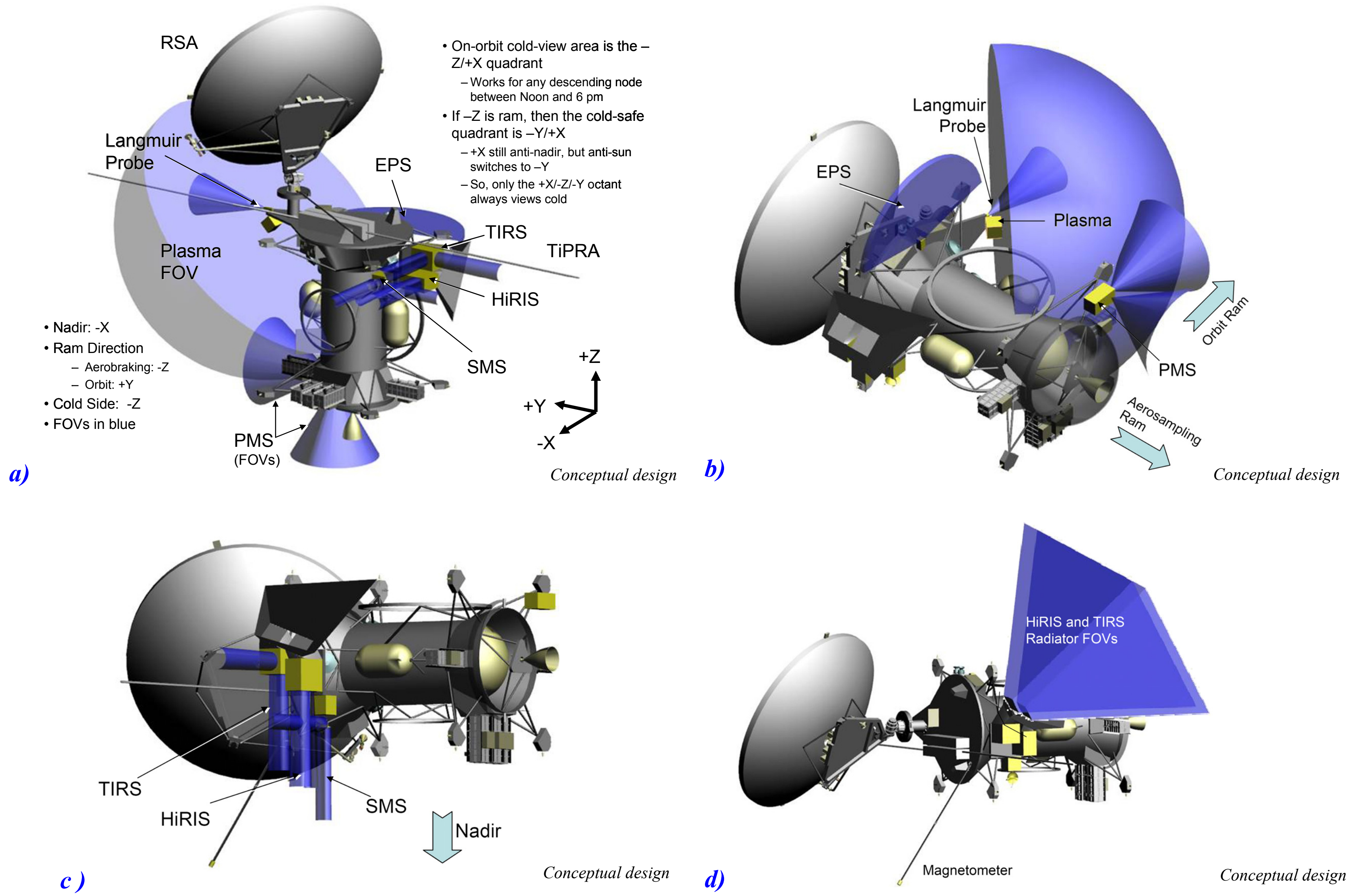


Figure 4.2-1. *Instrument placement on the spacecraft, with instrument and radiator fields of view: (a) overview, (b) plasma instruments, (c) nadir instruments, and (d) radiator FOVs and magnetometer boom.*

Table 4.2-1. *Preliminary pointing and timing requirements for Titan orbiter planning payload.*

Instrmt	Pointing Control (millirad, 3 sigma)	In-Flight Pointing Knowledge	Stability (microrad)	Ground Alignment	Timing (sec)
HiRIS	1	200 μrad	60/ 1 s	0.1 deg	0.02
TIRS	3	1 mrad	1,000/ 120 s	0.1 deg	0.02
SMS	5	1 mrad	1,000/ 60 s	0.1 deg	0.02
TiPRA	100	100 mrad	N/A	5 deg	1
PMS	5	2 mrad	1,000/ 1 s	0.2 deg	1
MAPP	10	5 mrad	1,000/ 1 s	1 deg	1
RSA	N/A	N/A	N/A	N/A	10

final timing data. This timing ensures that data taken on one orbit are correctly placed with respect to previous orbits. Final geo-location is performed during ground processing. Relative timing internal to an instrument, such as the time between adjacent along-track pixels, will be much more accurate. The timing requirements are not stressing, and the spacecraft bus, particularly with a USO on board, easily meets these requirements. If further definition of the instruments and their observing plans requires more accurate timing, the spacecraft bus can easily support sub-millisecond timing.

During the Aerobraking Phase of the mission, the PMS performs deep, *in situ* aerosampling of the atmosphere using the high mass range. The HiRIS captures cloud images when the spacecraft is near apoapsis. The SMS and TIRS perform limb measurements, and the MAPP instruments continue their survey of the Titan magnetosphere and its interaction with Titan's atmosphere. RF data during occultations provides additional data on the atmosphere. No TiPRA boom is deployed during aerobraking.

The nominal orbital altitude will be 1,500 km during the Circular Orbit Phase. The ground tracks for successive orbits are spaced 4.5° or about 200 km apart at the equator. The HiRIS imaging swath width is 50 km, so four complete global surveys, each 16 Earth days long, with interleaving ground tracks are required to complete a global map in one color. Section 4.6 describes each instrument's participation in the mission observing plan.

The instruments will be designed, built and tested to the expected environments. In reviewing the expected and predicted environments, all are typical of space missions and none incur additional risk or development complication for the instruments. The mechanical and pressure environments during launch, evaluated based on the potential launch vehicles, is typical of planetary missions and is similar to the environments experienced by the heritage instruments used to define the planning payload. Similarly, the thermal environments are typical. Because it is an ongoing development, the ASRG was subjected to additional analysis in terms of its expected impacts on instrument environment. For post launch, the ASRGs drive the vibration environment, which is predicted to be less than 5 N at the ASRG. Preliminary assessment indicates this would not be a problem for any instrument.

EMI requirements can be accommodated using established practices. Grounding of external surfaces reduces the effects of spacecraft charging. As discussed in the magnetometer section (§4.2.2.6), the spacecraft design would minimize the residual magnetic field. Again, the ASRG received additional analysis. At the outer magnetometer, the ASRG AC residual field is estimated to be lower than the magnetometer requirement, so it would not interfere with the magnetometer science. Preliminary analysis indicates that the ASRG residual fields would not affect any other instrument.

There are several opportunities for flight calibration of the instruments. Calibration will be conducted in flight during both cruise and in Saturn orbit. Calibrations are planned to occur at least every two years to monitor instrument performance trends and to uncover any anomalies. Calibration activities using the Earth, Moon, or both will be performed during at least one of the Earth flyby encounters but will be restricted to the outbound leg of the trajectory to avoid any conflict with activities associated with targeting of the flyby. Other cruise calibrations will use celestial targets for the remote sensing instruments. Once in Saturn orbit, Saturnian system bodies, which are well characterized by Cassini, are additional calibration targets.

4.2.1.2 Payload Resources

The resource requirements are based on analogous instruments on previously flown missions. **Table 4.2-2** presents the resource

***Table 4.2-2.** Titan orbiter planning payload heritage and resource requirements.*

	Name	Example Heritage	Mass (kg) CBE	Power (W) CBE	Downlink Data Rate (kb/s)	Description
HiRIS	High-Resolution Imager and Spectrometer (near IR)	CRISM, Artemis, VIMS, HiRISE, TBair, MOC, M^3	28.4	28 (one operating) or 32 (both operating)	77 (imager, 2 x 2 binning) or 225 (spec-typical)	Global surface mapping at 50 m/pixel in three colors (~2.0, 2.7, and 5–6 µm). Two spectral mapping bands 0.85 to 2.4 µm (5nm spectral resolution) and 4.8 to 5.8 µm (10 nm spectral resolution) supporting surface/atmosphere studies
TiPRA	Titan Penetrating Radar and Altimeter	SHARAD, MARSIS	11.0	25	20-30 (alt mode) or 280 (sounder) or 20,000 (burst)	>20 MHz global mapping of subsurface reflectors with 10 m altitude and 100 m depth resolution. Approximately 1 km x 10 km spatial resolution. Two dipole antennas: one used for Enceladus, then ejected; 2nd for Titan orbit.
PMS	Polymer Mass Spectrometer	RTOF portion of ROSINA	29.2	25 (low mass range) or 47 (high mass range)	4–48 (depends on data rate mode)	Upper atmospheric *in situ* analysis of gases and aerosol precursors—$M/\Delta M$ ~10,000 for masses up to 10,000 Da. Focus instrument for aerosampling down to 600 km. Better than 10^4 particles/cm^3
SMS	Sub-Millimeter Spectrometer	MIRO, ODIN, SWAS, and MLS	12.3	45	14	Direct winds from Doppler and temperature mapping from ~200–1000 km altitude; CO, H_2O, nitrile and hydrocarbon profiles; heterodyne spectrometer with scanned mirror.
TIRS	Thermal Infrared Spectrometer	CIRS, Mars TES	16.5	17	10	Organic gas abundance, aerosol opacity and temperature mapping 30–500 km. Passively cooled Fourier Spectrometer 7–333 µm. Spectral resolution 0.125–15 cm^{-1}.
MAPP	Magnetometer	MESSENGER, Cassini	2.2	3	4	Interaction of field with ionosphere: internal and induced field.
	Energetic Particle Spectrometer	PEPSSI, JEDI	1.5	2.5	5	Magnetospheric particle fluxes, ~10 keV to >MeV with 150° x 15° FOV.
	Langmuir Probe	Cassini, others	1.5	1	0.1	Swept voltage/current probe. *In situ* electron density and temperature, ion speed constraint, including during aerosampling.
	Plasma	PEPE	5.0	9	1–10 (depends on data rate mode)	Measures ion and electron fluxes at few eV to a few keV. $M/\Delta M$~10.
RSA	Radio Science + Accelerometer	Cassini, JUNO, many others	0.0	0	0	Lower stratosphere and troposphere temperature profile. Gravity field. Mass and power are zero because all hardware components are part of the spacecraft bus: USO, UST, and accelerometers.
Total			**107.6**	**181.5***	**135.1–20,600***	

Mass does not include the magnetometer boom, the radiator shades and the variable RHUs, which are carried in the structure and thermal sections of the spacecraft bus.
*The instruments are not operated at the same time, so the spacecraft is not required to supply the total payload power or total payload downlink rate.

requirements in the form of current best estimate (CBE) for each instrument and for the total payload. The contingency required for each instrument can be based on the maturity of the subsystems and components of each instrument. For mass, this method indicates that an additional 35 kg for the entire payload provides sufficient contingency and protection against mass growth during development. However, the allocation for the payload is 165 kg, which permits more than 50% growth above the current best estimates. This allocation drastically reduces the development risk, particularly for the maturity level of the instruments identified for this planning payload.

During orbit operations, neither the available power nor the downlink data rate support simultaneous operation of all instruments. As

described in §4.6, the observing plan shows that the science measurements can be acquired by operating several instruments at a time while the others are turned off or are in a lower-power mode. This means that the spacecraft bus is not required to supply the total payload power and data rate shown in **Table 4.2-2**.

The spacecraft telecommunications subsystem will support a downlink data rate of at least 140 kbps during the Titan science orbits using the Ka-band link with a 3 dB margin, into a DSN 34 m beam waveguide antenna, and 90% weather. With a 140 kbps data rate, the spacecraft can see the Earth (and transmit) for about 67% of each Titan orbit, and using two 8 hour DSN passes per day, the spacecraft downlink data volume will be almost 5.4 Gb per 24 hours. (The spacecraft completes about five orbits every 24 hours.) This data volume constrains the data return from high data rate instruments, so their raw data volumes are reduced through onboard compression, summing, and/or editing, and the highest data rate instruments would not be operated continually. The baseline 32 Gbit of storage allocated to science data mitigates the downlink constraint because high-rate data can be stored and then transmitted later. Representative data acquisition scenarios are presented in §4.6. Based on these current science scenarios, once the science data is returned to Earth and uncompressed, the equivalent daily science data volume would be over 7.3 Gb per 24 hours (when averaged over the entire 20-month Titan science mission). Therefore, the available power and downlink rate support global imaging and altimetry during the Titan science orbits, with periods of near-continuous fields and particles surveys, and coverage of selected target regions.

The power allocation for the payload provides a growth margin that is similar to the mass-growth margin. Section 4.6 describes operational scenarios that gather the required data without exceeding the power allocation. During the orbit operations, the instruments use an orbit average of 40 to 55 W, depending on the observing scenario. During orbit operations, Titan occults the spacecraft's view of Earth about 40% of the time, so the orbit average RF power is reduced, enabling the power-management scenarios that are described in §4.6.

The instruments are thermally isolated and use variable RHUs to maintain their temperatures above the nominal survival limit of –30°C. The instruments do not require additional power for survival heat. The instruments are shaded from the ASRGs, and the 80 K radiators have additional shades to protect them from direct view of the Sun and of Titan.

To protect the sensitive components during launch and during potential contamination or damaging events, several instruments have covers on their apertures, radiators, or both. **Table 4.2-3** shows which components are protected and where that protection is needed. In the current planning payload, only the HiRIS instrument has re-closable covers, which are extra protection during ring crossing and aerobraking. Future analysis might show that re-closable covers are not required or that they might be replaced with bakeout operations, but the covers are included in this payload to be conservative. No other instrument requires a cover during ring crossings or during aerobraking. All covers are failsafe, with redundant release mechanisms. All the instrument covers are included in instrument mass and power estimates.

The radiation environment is <15 krads total dose for the Baseline mission. The instruments will be designed to perform within this environment, which is typical of many flight missions. None of the instruments on the planning payload contains components that are radiation sensitive. None of the instruments require special shielding.

Table 4.2-3. *Identification of instrument components protected by covers.*

Instrument Component	Cover
HiRIS optics	Yes
HiRIS radiator	Yes
TIRS optics	Yes
TIRS radiator	Yes
SMS antenna	No
SMS radiator	No
TiPRA	No
PMS	Yes
Magnetometer	No
Langmuir Probe	No
Plasma	No
Energetic particles	Yes

Planetary Protection costing for the orbiter and its instruments is addressed in §4.11.7.6 and Appendix D. The project anticipated changes to planetary protection and assumed Planetary Protection Category III, which is over and above the study guideline requirements.

4.2.1.3 Payload Risk Assessment

The planning-payload instruments show that no new technology development is required to accomplish the science objectives. However, physical and electrical modifications of previous designs are required for most instruments to function within the context of the mission requirements. These modifications are included in mass and cost estimates. Custom-built components, or detectors built with a different form factor, are not considered new technology. Each instrument has strong flight heritage, if not for the entire system, then for the critical components. Risk is summarized in **Table 4.2-4**, which also mentions some mitigation options that can reduce mass, power, cost, or development time, should those become critical to the mission.

For some instruments, the mitigation options include a higher-heritage alternate design or component that still enables the instrument to meet its measurement requirements. The planning payload instrument could use this alternative as the baseline, but the proposal team considers the risk to be so low, and the

Table 4.2-4. *Summary of instrument risk and mitigation.*

Name	Description	Risk	Design Heritage	Changes from Heritage Design	Mitigation Options
HiRIS	High-Resolution Imager and Spectrometer (near IR)	Med-Low	Based on Cassini (VIMS), MRO (CRISM), and Chandrayaan (M3). Parameters from Team-X tool.	Different size optics. Lower-mass optics by using newer manufacturing techniques. Custom detectors.	Flight heritage exists, but at higher mass. Reducing pixel resolution to science requirement (50 m) reduces mass by about 3 kg.
TiPRA	Titan Penetrating Radar and Altimeter	Med-Low	Based on SHARAD and MARSIS. Lower mass.	Newer, lower-mass electronics. Single band.	Sufficient mass reserves carried to build at previously flown mass.
PMS	Polymer Mass Spectrometer	Med-Low	ROSINA. Testing complete (TRL 6) on prototype of changes.	More bounces, electronics that produce more-accurate timing.	Rebuild ROSINA, which is lighter but has lower resolution (M/ΔM of 3,000)
SMS	Sub-Millimeter Spectral Sounder	Med-Low	Heritage from MIRO, ODIN, SWAS and MLS, Herschel.	GaN power amplifiers, now under development and ready in 1–2 years.	Replace the GaN power amplifiers with GaAs amplifiers, which increases the average power by 2 W.
TIRS	Thermal Infrared Spectrometer	Med-Low	CIRS heritage. All light-weight components tested.	Smaller optics. High-Tc bolometers for longest wavelengths. Synthetic diamond beamsplitter. Pointing mirror from TES. More-robust mirror mechanism.	Carry mass reserve for components with higher heritage. Heritage detectors are less sensitive.
MAPP	Magnetometer	Low	Rebuild: MESSENGER, others	None required	Not required
	Energetic Particle Spectrometer	Low	Rebuild: New Horizons, JEDI	None required	Not required
	Langmuir Probe	Low	Rebuild: Cassini probe	None required	Not required
	Plasma	Low	Rebuild: PEPE or FIPS (add electrons)	None required for PEPE. For FIPS, add electrostatic sensor head for electrons	Carrying sufficient mass and power to rebuild either PEPE or FIPS.
RSA	Radio Science + Accelerometer	Med-Low	USO and accelerometers are COTS. Ka/Ka UST has some low-heritage components.	Lower-mass USO. UST combines several wavelength bands in a single package.	Existing transponders, without Ka/Ka capability, add mass and add risk (lower data quality) to gravity investigation.

Notes:

1. Low risk means minimal changes to a flight-proven instrument.
2. Medium-Low risk means that design is based on flight heritage but the instrument is repackaged or that some newer-technology components replace older, lower-performing components.

benefit to be so clear, that the baseline includes the item in question. The GaN power amplifiers on the SMS are a good example.

Alternative instrument concepts and techniques might be selected via the AO process to meet the mission objectives and measurement requirements as stated in the final AO. Some of the descriptions of planning-payload instruments include discussions of alternative techniques, which reinforce the feasibility of meeting TSSM science requirements.

With few exceptions, the individual instruments in the planning payload do not have internal redundancy. This is entirely the result of keeping the mass as low as possible. As part of the Phase A activities, redundancy could be assessed and added if deemed necessary for vulnerable electronic components.

Meaningful descopes within each instrument that recover more than a few kilograms and/or a few watts and reduce costs are not apparent for the planning payload without significantly impacting the science return. As a result, instrument descopes for the planning payload are not specifically identified at this time because it would be premature to do so until the actual flight instruments are selected in Phase A. The descope strategy described in §4.11.7.8 makes use of only engineering descopes and preserves Level 1 science.

4.2.2 Instrument Descriptions

4.2.2.1 HiRIS

The High-Resolution Imager and Spectrometer (HiRIS) consists of an IR camera plus an IR imaging spectrometer that share common electronics, thermal radiator, and some structure. **Figure 4.2-2** is a block diagram for HiRIS and **Table 4.2-5** lists the top-level performance parameters

IR Camera

The IR camera acquires images in three of the methane transmission windows, approximately centered at 2.05, 2.73, and 5.35 µm with 0.16, 0.16 and 0.9 µm bandpasses, respectively. It has an Instantaneous Field of View (IFOV) of 16.7 µrad yielding a pixel footprint on the surface of 25 m from a 1500 km altitude orbit. The detector is 2048 pixels wide covering a nadir swath 50 km wide on the surface. The detectors are made of HgCdTe and are passively cooled to 70 K for good SNR.

The camera uses a pushbroom imaging approach to facilitate mapping from the circular science orbit. Three separate line-array detectors with superimposed bandpass filters provide the three-color coverage. Distant imaging at greater distances outside the circular science orbit is accomplished using slow, smooth

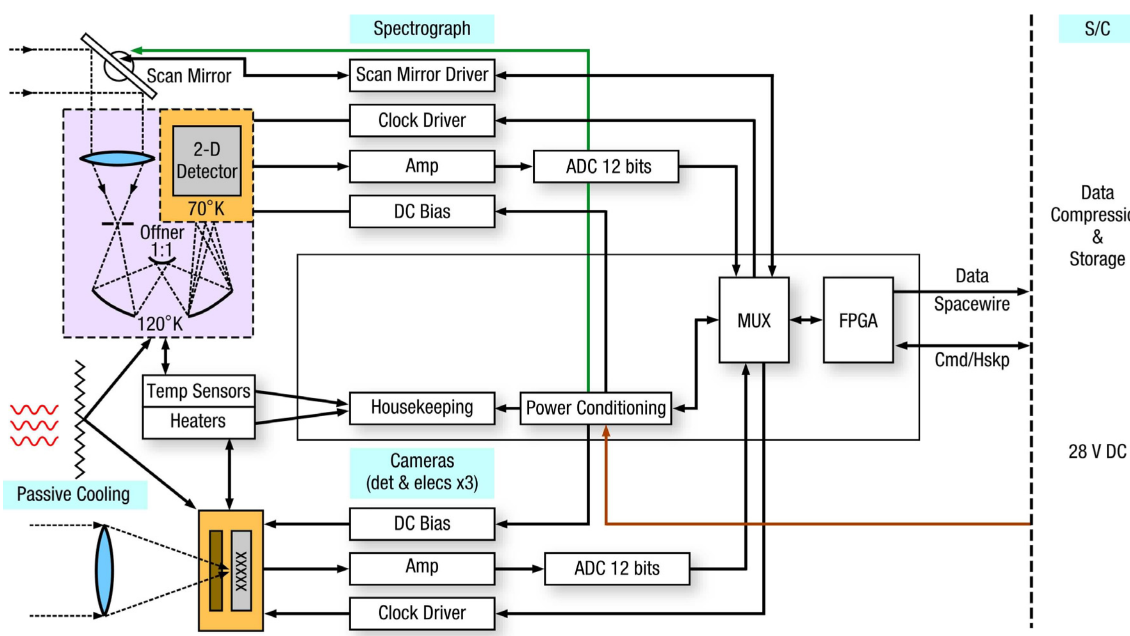


Figure 4.2-2. *HiRIS block diagram.*

Table 4.2-5. HiRIS performance.

Instrument	Parameter	Capability
Camera	Spatial resolution	50 m from 1500 km altitude
	IFOV	16.7 µrad (normally 2 x 2 binned)
	Spectral bands	2.05±0.08 µm, 2.73±0.08 µm, 5.35±0.45 µm
	Swath width	50 km from 1500 km altitude
	Integration time	53 ms (2 x 2 binned mode)
	SNR at zero phase	147 in 5.35 µm band, 2 x 2 binned
	Aperture	30 cm
	f/#	f/3.6
Spectrometer	Spatial resolution	250 m from 1500 km altitude
	IFOV	83.5 µrad (normally 2 x 2 binned)
	Spectral range	0.85–2.4 µm and 4.8 –5.8 µm
	Spectral resolution	5 nm in SWIR, 10 nm in MWIR
	Spectral channels	410
	Integration time	133 ms minimum; 267 ms 2x2 binned no IMC; longer with IMC using scan mirror
	SNR at zero phase	138 with 10x IMC and 2 x 2 binning
	Aperture	9 cm
	f/#	f/2.4

spacecraft scanning to build up spatial coverage. However, a framing camera approach could also be used. This approach would make distant observations easier and would allow use of the same type of detector for both the camera and the spectrometer but would require either separate area-array detectors to provide the color coverage or the addition of a filter wheel.

The camera optics include a 30 cm diameter aperture and operate at f/3.6. The IR camera is based on heritage from the Mars Global Surveyor (MGS) Mars Observer Camera (MOC) (Malin et. al. 1992, and Malin and Edgett 2001), the Mars Reconnaissance Orbiter (MRO) High-Resolution Imaging Science Experiment (HiRISE) (McEwen et. al. 2007), and the *Cassini* Visual and Infrared Mapping Spectrometer (VIMS) (Brown et. al. 2004). The camera swath width allows complete global coverage of Titan with about 325 swaths or in about 65 days of continuous dayside mapping.

Camera data are normally binned into 2 × 2 pixel samples for mapping; unbinned data may be taken of selected areas to provide maximum spatial resolution. For the orbital ground speed of 0.938 km/s at 1500 km altitude, the maximum exposure time for one 2 × 2 binned pixel of smear is 53 ms, which will provide adequate SNR (~100 near the sub-solar point) for each channel. Twelve-bit data encoding is assumed. Real-time data reduction by a factor of 3 is envisioned via a standard lossless data compression algorithm performed within the instrument FPGA. The data are transferred to the spacecraft C&DH at an output data rate of 307 kbps per color in the full-resolution (25 m/pixel) mode and at 77 kbps per color in the typical 2 × 2-pixel binned mode. Data rates to onboard memory and to the ground can be tailored to available rates and volumes by adjusting the instrument duty cycle, the mapping coverage, the number of colors used, and the degree of pixel binning.

During Enceladus encounters, global images will be acquired from ~15,000 km range and will yield a spatial resolution of ~0.5 km/pixel. Acquiring these data will require smooth spacecraft scanning to build up spatial coverage. During close flybys, data will be acquired from a range of ~600 km yielding a spatial resolution of 30 m/pixel and a swath width of 30 km. At 1000 km the ground speed will be 2.0 km/s, allowing a maximum exposure duration of 15 ms for one binned pixel of smear, yielding a SNR of ~75 at 5 µm. At the shorter wavelengths where the solar irradiance is greater, the SNR will be much higher. During these closest flybys, data will need to be recorded for all three wavelengths simultaneously.

IR Spectrometer

The IR Spectrometer (IRS) covers a wavelength range of 0.85 to 2.4 µm with a spectral resolution of 5 nm and a second range of 4.8 to 5.8 µm with a spectral resolution of 10 nm, yielding a total of 410 spectral channels. In typical operation, up to 300 spectral channels located within the atmospheric methane transmission windows (including the wings of the windows) will be selected for downlinking. The spectrometer is an optically fast Offner

imaging spectrometer with high spectral uniformity across the detector. The foreoptics have a 9 cm aperture and operate at f/2.4. The optics are cooled to 120 K. The 1024 × 1024 pixel HgCdTe detectors are passively cooled to ~70 K to yield acceptable signal-to-noise performance. The spectrometer IFOV is 83.5 µrad yielding a footprint of 125 m/pixel from an altitude of 1500 km. The swath width at nadir is 128 km across track.

Adequate SNR and proper spectral sampling requires 2 × 2 pixel binning with an effective footprint of 250 m from 1500 km. A scan mirror is located in front of the optics for use in image motion compensation (IMC). Use of IMC in the 1500 km science orbit allows integration time to be increased to yield adequate SNR (>500:1 at 2 µm and >150:1 at 5 µm). Using IMC to increase the integration time to 2.67 s and acquiring coverage of 512 binned pixels along track to produce a square image requires about 23 minutes with a range of emission angles of ±34°. Alternatively, the scan mirror can be fixed to obtain extended along-track swaths using nadir pointing; however, 8 × 8 pixel spatial binning (1 km samples on the surface from 1500 km altitude) would be required in this mode to achieve adequate SNR while maintaining full spectral resolution. Observations of distant objects during the Saturn Tour Phase of the mission (e.g., observations of Enceladus) will also be possible by using the scan mirror to build up spatial coverage. During such imaging it will be possible to return all 410 spectral channels for each pixel. The spectrometer draws on heritage from the Chandrayaan Moon Mineralogy Mapper (Mouroulis et al. 2007), Cassini VIMS, and the Mars Reconnaissance Orbiter Compact Reconnaissance Imaging Spectrometer for Mars (CRISM).

At 12 bits/pixel, the raw output data rate from the spectrometer is 38 Mbps for output of 410 spectral channels unbinned. Channel selection is performed within the instrument. A variety of spatial and spectral editing and binning modes will be implemented in the instrument FPGA along with lossless data compression. As for the camera, data rates to onboard memory and to the ground can be tailored to available rates and volumes by adjusting the instrument duty cycle, the mapping coverage (swath width and length), the number of spectral channels returned, and the degree of pixel binning. A typical scheme might involve 10× IMC, 2 × 2 binning, and spectral editing down to only 300 channels yielding an output rate for compressed data of ~225 kbps. One interesting option for cloud studies would be to bin pixels both spatially and spectrally to produce broad bandpass images in selected bands while covering a wider FOV than the IR camera can.

Spectra of Enceladus will be acquired at two spatial resolutions: 1 km/pixel providing global coverage, and regional coverage at 300 m/pixel. Lower resolution data will be acquired at a distance of 6,000 km and will require smooth spacecraft scanning for the second spatial dimension. The higher-resolution data will be acquired from a range of ~1,800 km with a ground-track speed of 1.2 km/s With 10× IMC and 2 × 2 binning, exposure durations >2.0 ms will be possible, yielding an adequate SNR.

Accommodation Requirements

The HiRIS volume is estimated to be 30 × 50 × 60 cm for the optics and detectors plus a 7 × 15 × 20 cm electronics box. The mass is estimated to be 28.4 kg. The power interface from the spacecraft is 28 V DC. When operating either the camera or spectrograph separately, the average power is 28 W; when operating both simultaneously, power is 32 W. The data interface is provided by SpaceWire to handle the occasional high raw output data rates. The instrument is thermally isolated from the spacecraft. Cooling is provided by a passive radiator viewing approximately along the +X, -Y, -Z unit vector with a FOV of about 0.3 sr to dark space. Re-closable covers are included for the optics apertures and the radiator to protect against contamination during launch and aerobraking.

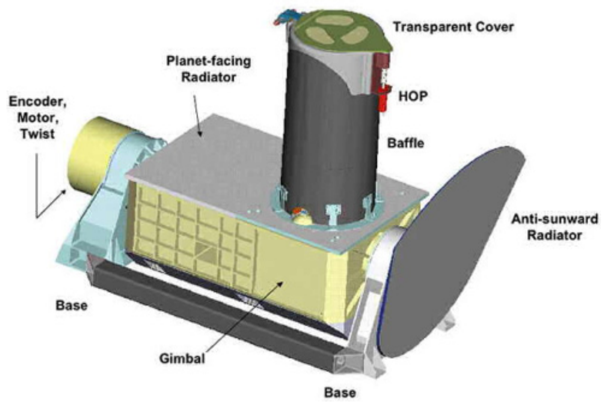
The instrument must have a clear FOV of 20°. The instrument must be aligned to within 2 mrad of nadir and with the detector array lines within 2 mrad of normal to the ground track when in the circular science orbit. This alignment is sufficient to enable coordinated measurements with other nadir-pointed instruments without producing smear due to pointing and yaw errors. In-flight observations will determine HiRIS alignment to the limit of the ACS accuracy, which is better than

150 μrad. Pointing stability of <60 μrad/s is required. Standby power of 12 W is required to maintain temperatures within thermal limits when not operating. No delay for thermal stabilization is required to resume operations after being in standby. When HiRIS is off, the survival temperature for the electronics is –30°C.

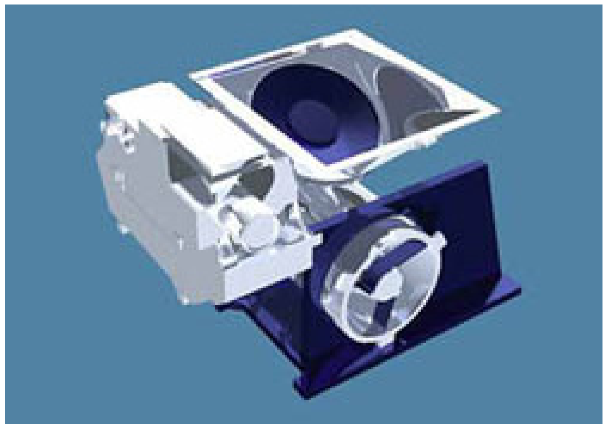
The HiRIS mass estimate is derived from the MOC camera (24 kg) and M^3 spectrometer (8 kg) analogy instruments. M^3 is modified by increasing the optics speed from f/3.5 to f/2.4 and adding a scanning mirror and optics and radiator covers for a mass increase of 5 kg. Combining these two instruments into a single package is estimated to result in mass reductions of 3 kg in mechanical structure, 2 kg by sharing a thermal radiator, and 3.6 kg in shared electronics such as the FPGA, power conditioning, thermal control, and data interface. The HiRIS power estimate of 28 W is based on the average of the analogy instrument power levels for MOC (19 W), VIMS (26 W), and CRISM (38 W) and a JPL Team X conceptual design model estimate of 27 W for the IR camera. Since most of the HiRIS electronics and thermal control are shared between the camera and the spectrometer, the difference in power to operate either instrument is insignificant, and the increase in power required to operate both instruments simultaneously is estimated at an additional 4 W.

Heritage

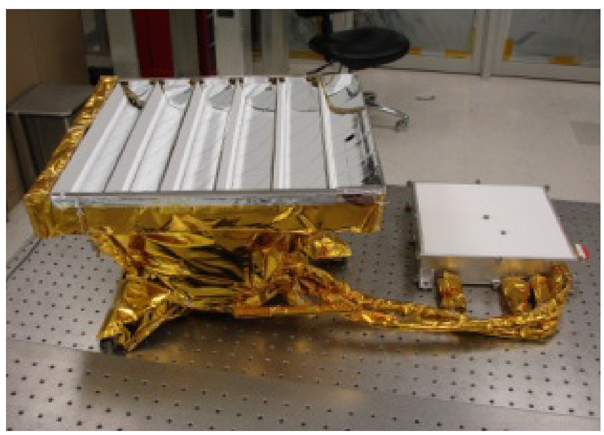
Figure 4.2-3 shows some of the heritage instruments that form the basis of the HiRIS design. No new technology is required for HiRIS; however, the packaging of the various components is new and the detectors will be custom procurements. The low-mass optics are also custom designs, but well within the capability of current technology. If a lower-mass instrument is necessary, then increasing the imager IFOV from 25 m to 50 m will reduce the mass by 3 kg. This modification eliminates some operational flexibility and reduces the maximum resolution of the imager, but still meets the minimum science requirements.



***(a)** CRISM*



***(b)** VIMS*



***(c)** Moon Mineralogy Mapper*

***Figure 4.2-3.** HiRIS draws from several successful instruments: (a) CRISM, (b) VIMS, and (c) the Moon Mineralogy Mapper.*

4.2.2.2 Titan Penetrating Radar and Altimeter

The subsurface sounder instrument for the planning payload is the single-band Titan Penetrating Radar and Altimeter (TiPRA). This instrument is based on successful sounders that have flown on missions to Mars: the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) instrument (Seu et al. 2007) on board ESA's Mars Express and

the Shallow Radar (SHARAD), a higher-frequency instrument on MRO. MARSIS (Picardi et al. 2005) is a multiband, synthetic-aperture, orbital sounding radar that operates in four 1 MHz frequency bands between 1.3 and 5.5 MHz. At an operating frequency above 20 MHz, the TiPRA can have sufficient bandwidth to produce better altitude resolution and smaller footprint. This system is more similar to SHARAD and has an advantage that the required length, 10 m, of the dipole antenna is shorter than the lower-frequency alternatives. The higher frequency will provide high spatial resolution (footprint and depth) for studying the subsurface above 3 km depth at high (10 m) vertical resolution. For measurements at Enceladus, the deeper sounding depth reduces the veridical resolution to 100 m, depending on the specific range (see Phillips et al. 2008 for an example of instrument capability).

TiPRA will have a minimum instantaneous bandwidth of 10 MHz. This bandwidth corresponds to a range resolution close to 10 m in free space and better than 10 m in other mediums of interest such as ice. The horizontal resolution of the instrument in the cross track direction is ~5 to 10 km assuming an operation altitude of 1500 km, and along track resolution is Doppler-sharpened 1–2 km. The SHARAD instrument nominally operates at 700 Hz pulse repetition frequency. SHARAD transmits a chirp that spans 10 MHz over an 85 µs period. For TiPRA, peak transmitted power out of the 10 m dipole antenna is ~100 W, which is more than the 10 W SHARAD radiated power because of the Titan spacecraft's higher altitude. The radar's duty cycle is low (~1%), so the overall DC power consumption is ~25 W. This actual power consumption can be lowered further by relying on an ASIC-based on-board processor. **Table 4.2-6** contains additional specifications for the TiPRA instrument.

Coherent azimuth sums are performed on-board with a resulting signal-to-noise ratio for a simulated Titan surface of 25 to 45 dB at the operating altitude range of 1500 km. The wide range in the estimate of the SNR is due to uncertainties in the scattering properties of the surface and in the dielectric constants. This SNR is approximately the same performance as SHARAD at Mars owing to the higher operating altitude but at a 10 dB higher transmitted power than SHARAD. The SNR is further enhanced by coherent azimuthal sums, which lower the cross-track spatial resolution to 10 km. Given that targets of interest for subsurface sounding (such as the low-latitude sedimentary basins, or the polar hydrocarbon seas) have horizontal extents of hundreds of km, a 10 km resolution is adequate.

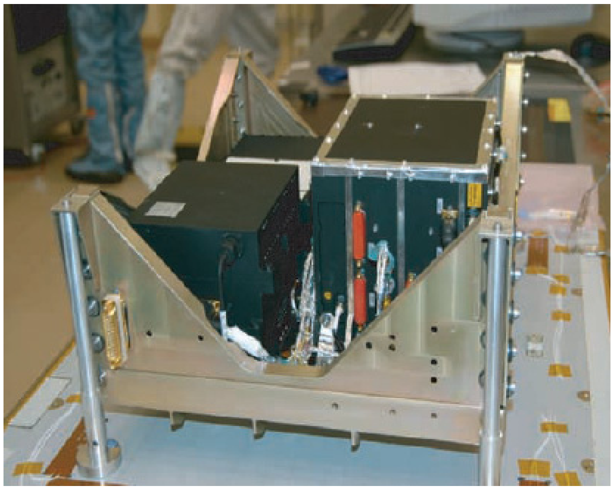
Table 4.2-6. *TiPRA performance.*

Parameter	Value
Mass	11 kg
RF transmitted power	100 W
Pulse repetition frequency	400 Hz
Radar exciter chirp	250 µs
Orbit Average Power	25 W
Center frequency	>20 MHz
Bandwidth	10 MHz
Spatial resolution-lateral	1–10 km
Vertical resolution altimeter	<10 m
Vertical resolution sounder-Titan (shallow)	<10 m
Vertical resolution: deep-penetration mode	100 m
Depth penetration-Titan (high-resolution mode)	3-5 km
Depth penetration: deep-penetration mode	20–50 km
SNR (surface return echo)	40–50 dB
Data Rate-Altimeter mode	20–30 kbps
Data Rate-Sounder mode	~280 kbps
Vertical resolution sounder-Enceladus (deep)	100 m

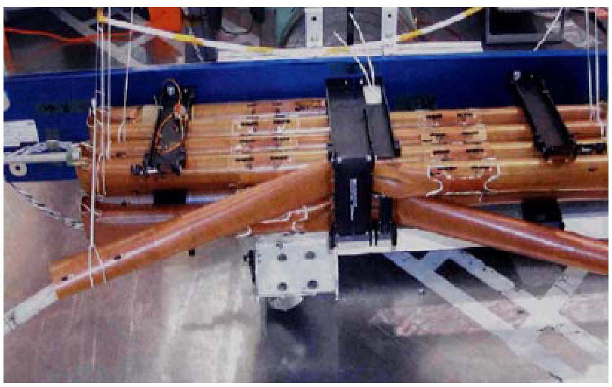
Currently, the Titan surface models—which are not based on altimeter data with high spatial resolution—are too preliminary to provide good surface-clutter estimates for TiPRA measurements. However, on Titan, there are many areas where there is no ambiguity due to the surface being very smooth. Moreover, in areas of high clutter, there are techniques that use parallel tracks to discriminate between surface clutter and depth return; examples of these techniques were demonstrated using SHARAD data in areas where MOLA is not sufficiently high res to detect all clutter. For Enceladus, some of the deep returns will not be confused with surface clutter, which is stronger at near range.

Accommodation Requirements

TiPRA employs a 10 m antenna forming a dipole oriented perpendicular to the nadir axis and either parallel or perpendicular to the velocity vector. The SHARAD-style antenna consists of simple conducting wires supported by a 3.8 cm diameter fiberglass tube that is folded and compressed into a compact box prior to deployment. **Figure 4.2-4** shows the electronics and stowed antenna from SHARAD. Alternate antennas are available,



(a) SHARAD electronics



(b) Folded antenna

Figure 4.2-4. *SHARAD electronics and folded antenna (Seu et al. 2007).*

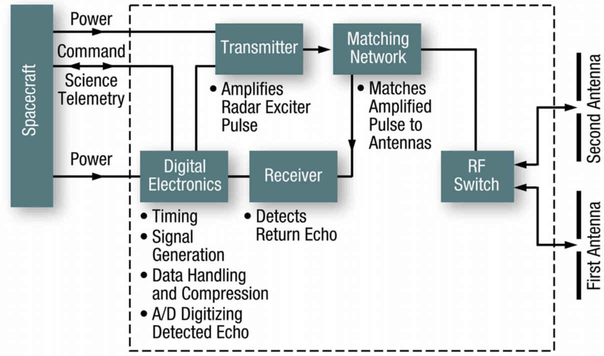


Figure 4.2-5. *TiPRA functional block diagram. Physically, the TiPRA consists of the antenna and electronics packaged in two or three units.*

including compressed-spring antennas used on the Solar Terrestrial Relations Observatory (STEREO). For Titan, the antenna is mounted on the orbiter top-side deck and is self-deployed upon release by pyro-mechanisms.

To enable use of TiPRA at Enceladus and to capture the potentially remarkable data—a direct measurement of the ice thickness that is not based on models—TiPRA has two complete dipole antennas. The first antenna is deployed after the low altitude Titan 5 flyby and captures Enceladus data during flybys. This first antenna is then jettisoned so that it does not create any risk during aerobraking at Titan. The antenna will be jettisoned following the last Enceladus flyby and prior to the low altitude Titan 14 flyby (**Table 4.3-7**) such that the antenna's trajectory does not pose any planetary protection risk to either Enceladus or Titan. The second antenna is then deployed once the spacecraft is in circular orbit around Titan. To ensure no interference with the second antenna, TiPRA contains an RF switch between the antennas. The second antenna, along with the ejection system and all secondary hardware and electronics, has a mass of 2 kg. This approach is lower mass and lower risk than constructing a retractable antenna or a single antenna that could survive aerobraking.

Each of TiPRA's 10 m dipole antennas is physically two 5 m poles, and each dipole has a stowed volume of 1.5 × 0.3 × 0.2 m.

The TiPRA functional block diagram is shown in **Figure 4.2-5**. The transmitter matching network box is located close to the antenna. The digital electronics and receiver are located in a separate box, which could be remotely located. The two boxes can be combined to save mass if needed. The digital electronics contain an ASIC-based processor to reduce mass and power. The TiPRA transmitter is a HF-band solid state transmitter capable of operating at 400 W peak transmit power. The transmitter system delivers the RF energy to the dipole antenna through a matching network system.

Electromagnetic interference must be considered in the spacecraft design from the start. These requirements have been flowed down to all spacecraft and science subsystems. Special care must be taken in shielding cables and other subsystems. The EMC plan to accommodate the radar should be in place from the beginning stages of the spacecraft design. There are no unusual or difficult requirements

as long as the EMC implications are considered during the design and development of the spacecraft.

There are three operating modes for the TiPRA. Most operation is in the altimetry mode, which has a data rate of 20–30 kbps and will be gathered over the entire surface. Since its data rate is ten times higher, the sounder mode will be used in more of a targeted-type operation to examine geological forms of interest. Section 4.6 on operations shows that there is sufficient downlink available to capture the interesting geological features with a factor-of-three margin, even with conservative assumptions.

The final mode is the burst mode, where TiPRA sends the raw data rate of 10 to 20 Mbps. The spacecraft bus accommodates this high rate with a SpaceWire connection to the C&DH processor. Burst mode is used for short durations, approximately 30 s, for diagnostics on the instrument, to verify the compression algorithms, and to allow on-ground focused processing of the data, providing the highest resolution images of specific areas.

The TiPRA instrument contains 256 Mb of internal non-volatile memory. TiPRA relies on its own processing capability. Range compression, pre-summing, Doppler filtering, data averaging, and resampling are done internal to the instrument to reduce its normal output data rate to ~280 kbps.

For non-TiPRA orbits, the instrument will be off. TiPRA requires standby power of 15 W for 15 min to warm up from a cold start.

Heritage

The TiPRA mass and power are derived from existing instruments, primarily SHARAD and MARSIS. The antenna and cable mass are scaled for the antenna size. The electronics (transmitter, receiver, and digital processor) are based on SHARAD, but modified for the higher transmitted power and by replacing the DSP processor with an ASIC. The power required by the TiPRA transmitter is approximately 4 W higher than SHARAD, but the digital electronics use approximately 4 W less due to the improved processer.

The risk in TiPRA development is the low mass and power nature of the instrument. In order to achieve the expectations for power and mass, an ASIC-based or FPGA-based processor is required. SHARAD contained a DSP-based on-board processor that was 2–3 kg heavier than required by currently available technology. Since TiPRA's required processing is well within the capability of current ASIC technology, the residual risk is in accomplishing the development on schedule. With a planned launch in 2020, ASIC development is unlikely to be an issue.

4.2.2.3 Polymer Mass Spectrometer (PMS)

The mass spectrometer for the planning payload is the PMS, a multiple-bounce time-of-flight (MBTOF) mass spectrometer. The PMS is derived from the Rosetta ROSINA RTOF and uses two time-focusing ion sources and a sophisticated gas inlet/ aerosol sampling system to make high mass-resolution ($M/\Delta M>10{,}000$), high sensitivity (<5 ppb) measurements of Titan's atmosphere and ionosphere.

Three gas inlets feed two conventional electron bombardment ion sources (Waite et al. 2005; Balsiger et al. 2007). The first inlet feeds an "open" ion source used to measure ambient ions (positive and negative) and neutral atoms, including reactive ones. These species travel through the source without contacting surfaces that might cause chemical reactions that invalidate the measurement. The second inlet feeds non-reactive neutral species into an antechamber (reactive neutrals do not progress past the antechamber) from which they are leaked into a "closed" ion source. The third inlet feeds an aerosol sampling system designed to collect aerosols from 0.002 to 1 µm in size and pyrolyze them to determine their monomer structure. Aker valves and manifolds for the gas inlet / aerosol sampling system are flight proven.

A storage-type source is used as the closed ion source. It traps ~100,000 ions in a potential well created by the ionizing electron beam. Once the well is filled, a fast (for example, +300 V, 5 ns) pulse applied to the back of the source ejects ions into the MBTOF packet. The spectrograph processes spectra as fast as the ion trap fills, so the duty cycle of the MBTOF can approach 100%. When operating at the nominal rate of 10,000 spectra per second, the storage trap fills when the ambient pressure is greater than 10^{-7} Torr. For the open source, the PMS uses an orthogonal injection ion source

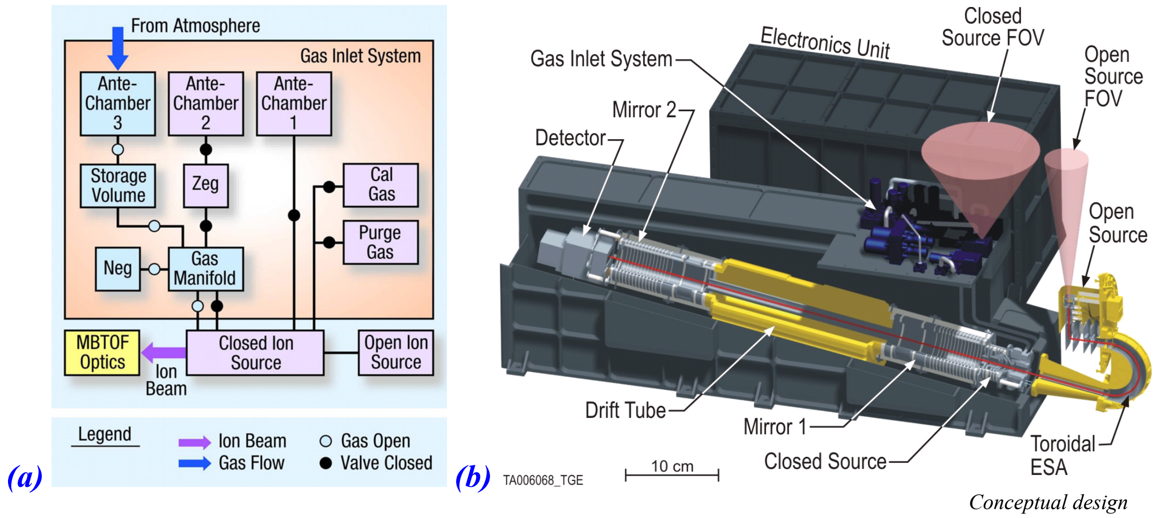


Figure 4.2-6. (a) Block diagram and (b) drawing of the PMS.

(Balsiger et al. 2007), which compensates for the energy dependence of ions with different masses entering the source at orbital speeds (approximately 0.04 eV/amu).

Negative ions are measured using the open source by switching all of the polarities on potential surfaces. These surfaces include the electrostatic ion push/pull extractor, the electrostatic analyzer plate, the drift tube, the mirrors, and the detector. This is accomplished using bipolar power supplies, which adds about 2 kg and 2 W to the monopole power supplies.

Time-focused ion packets enter the MBTOF through mirror 1 (**Figure 4.2-6**), which is gated off and then on to let the ions pass. The ion packets then travel through the flight tube until they encounter mirror 2 and are reflected. Ions then return to mirror 1, where they are again reflected, repeating the bounce cycle as many times as desired. For ions of mass M with energy U bouncing N times between mirrors separated by distance L, then

$$M/\Delta M = (NL/\Delta t)(M/2U)^{1/2}$$

where Δt is the width of the ion packet. This shows that by maintaining time focus increasing N increases resolution up to a practical limit N~25 corresponding to M/ΔM~15,000 for MBTOF. Once the desired number is reached, the potential on mirror 2 is lowered, allowing ions to reach the detector. MBTOF mirrors and lenses maintain $\Delta t \approx 5$ ns over 25 bounces with <50% loss of intensity.

Since N can be selected at will, low-resolution (LR) and high-resolution (HR) modes can be defined that take full advantage of this flexibility. In LR mode, ions execute no bounces, producing a complete survey mass spectrum at a resolution of ~500. In HR mode, multiple bounces are employed to increase resolution. The LR and HR operational modes can be alternated in any desired pattern.

PMS uses a 24 stage discrete dynode MagneTOF™ detector, which has the advantage of two signal outputs: a low-gain (10^3) analog pickoff and high-gain (10^8) analog pickoff. A 1 GS/s ADC digitizes both the low-gain waveform and the high gain signal. The combination results in a total dynamic range of 3×10^5 per spectra, which is essential for measurements of neighboring isotopic species with widely varying abundances. Spectra are collected and co-added at a rate of 10 kHz, producing an effective dynamic range that exceeds the mission requirement of 10^8. The detector and the ADC system have been prototyped and tested at detector counting rates up to 2 MHz.

By co-adding spectra, the PMS data rate is tailored to its allocation. The highest data rates are best when the densities and composition are expected to have the highest variability such as during flybys through the plumes of Enceladus, or during deep-atmosphere sampling at Titan. During initial operations, the three inlet systems will each collect data for

1/3 of each second. Depending on early results and on the science goals of a particular observation, the science team can vary either the integration period, the allocation among the three inlet systems, or both.

During the Aerobraking Phase of the mission, PMS will use the full mass range, up to 10,000 Da. Once in circular orbit, where the heaviest polymers are absent, using the lower mass range, up to 500 Da, reduces power consumption from 47 W to 25 W.

To maintain a high degree of chemical cleanliness, the ion sources, optics and detectors are mounted in a single vacuum enclosure that is baked out prior to launch and then sealed by separate captive covers over each gas inlet. The covers, which use the same mechanism as the Rosetta ROSINA Reflectron Time-of-Flight are released following orbit insertion. Calibration and purge gases are carried in separate cells and can be fed to either ion source.

The Titan atmosphere itself is a potential source of contaminants. PMS includes heaters for out-gassing and bake-out. These heaters raise the temperature of the source chamber and antechamber to remove material that may have become attached to the walls.

Accommodation Requirements

PMS is mounted on the Titan orbiter spacecraft so that it has clear view of both ram directions. To provide a clear view in the –Z (aerobraking ram) direction, the PMS must be located near the –Z end of the spacecraft. Since this is the area of the spacecraft where the main engine and the ASRGs are located, the PMS is closer to these parts of the spacecraft than is desired in an ideal layout. (See the spacecraft bus description, §4.4, for the decisions and design that drove the spacecraft configuration and ram directions.) The PMS can be isolated from the ASRG mechanical and thermal effects, but the PMS performance may be degraded (slightly higher background noise) due to radiation. The specific effects and any required mitigation depend on the final technology chosen for the PMS, but the experience of Cassini indicates that mass spectrometers can function well in the vicinity of radioisotope power supplies. The proximity of the main engine means that the PMS cannot operate effectively during ΔV maneuvers, but no PMS operations are planned during these events. If future analysis indicates that thruster contamination will have a lasting effect on PMS, then the final PMS design can include a multiple-use mechanism for the PMS contamination cover such as the mechanism on ROSINA. The spacecraft attitude-control thrusters are located at both +Z and –Z areas of the spacecraft. This places some attitude-control thrusters near the PMS, and the PMS data will be affected if the thrusters are used while the PMS is taking measurements. However, the spacecraft design may not require attitude control thrusting during aerobraking. If thruster use is unavoidable, only the thrusters at the +Z end of the spacecraft, away from PMS, will be used. This approach reduces and possibly eliminates PMS contamination during low-altitude sampling. Thruster use for momentum-dumping operations (while in circular orbit) will be planned, mitigating their effect on PMS science.

To accommodate the two FOV directions, the PMS is mounted on a rotating platform that increases the PMS mass by 3 kg (prior to adding contingency). This stepper-motor mechanism is based on the Cassini Plasma Spectrometer (CAPS) rotating mechanism on Cassini.

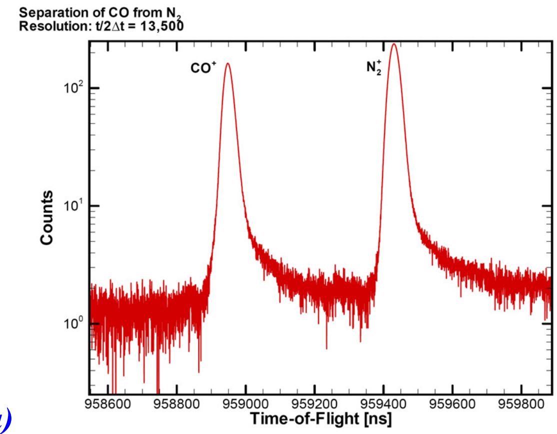
The closed ion source has unobstructed 60° half-angle FOVs centered on each gas ram direction (**Figure 4.2-1b**). The open source has 7.5° half-angle FOVs in the same directions. Special attention will be given to spacecraft attitude control (§4.4) to ensure that the apparent gas ram vector is within the open source FOV during periapsis passes. Electrostatic cleanliness requires that surfaces within 1 m of INMS are conductors held at spacecraft ground potential.

Heritage

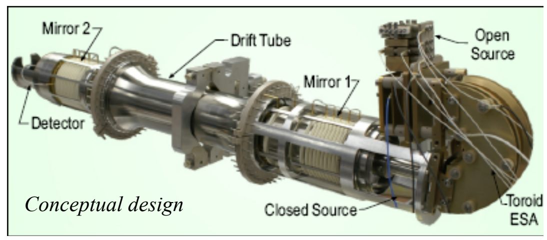
The PMS is based on the Rosetta Rosina Reflectron Time-of-Flight (RTOF) now on its way to a comet. Its characteristics are summarized in **Table 4.2-7**. The enhancements include multiple bounces and improved dynamic range of the detector. To test the enhancements that are required for PMS, SwRI has built and successfully tested two MBTOF prototypes developed under a Mars Scout Phase A study. The result is a high precision prototype incorporating all key performance features required

Table 4.2-7. *PMS characteristics and performance summary.*

Instrument Type		
Multiple bounce time-of-flight (MBTOF) with storage ion source		
Mass	**Power**	**Data Rate**
29 kg	25W / 47W	2.5-60 kbps
Characteristics		
Source	Dual ion sources with redundant filaments	
Detectors	Discrete dynode SGE MagneTOF™	
TOF Measurement	Rad hard custom 1 GS/s ADC with 2 GHz Rad hard time to digital converter (TDC)	
Parameter	**Requirement**	**Capability**
Dynamic Range: Detector Signal acquisition	 $>10^7$ $>10^8$	 $3\text{x}10^7$ 3×10^8
Mass/charge Range	1 to 10^4 amu/e$^-$	1 to 10^4 amu/e$^-$
Mass Resolution, M/ΔM	>10,000	>13,000
Sensitivity	Open source $<10^4$ ions/cm^2 sr sec; Closed source $<10^5$ particles/cm^3	Open source 10^3 ions/cm^2 sr sec; Closed source 10^4 particles/cm^3
Angle Response (FWHM)	7.5° open source; >45° closed source	7.5° open source; 60° closed source
Time Resolution	<0.04 s	0.01 s



(a)



(b)

Figure 4.2-7. *(a) Spectra obtained June 2008 from (a) PMS prototype.*

of a flight instrument including gas inlet system, both ion sources, high voltage pulsers, complete TOF optics and the detector all operating in a vacuum (space-like) environment. Thus, all essential PMS technologies and functional capabilities in this instrument have been demonstrated.

Data in **Figure 4.2-7a** were taken with the PMS prototype (**Figure 4.2-7b**). The figure demonstrates the resolution performance of the instrument by showing separation of the mass doublets $^{12}C^{16}O/^{14}N^{14}N$. This resolution of >13,000 is sufficient to resolve other doublets such as $^{13}C^{16}O/^{14}N^{15}N$ and $^{13}C^{16}O^{17}O/^{12}C^{16}O^{18}O$. Other tests include ^{126}Xe abundance measured in air (8 parts per billion with S/N >3) using a 12-bounce spectrum with 1 s accumulation. Thus, tests of the prototype of this PMS instrument demonstrate sufficient resolution and sensitivity to meet the Titan orbiter science requirements.

The mass estimate of 29.2 kg is based on adding the following to the 15 kg mass of ROSINA: 3 kg for the actuator, 2.5 kg for negative ion electronics, 2 kg for additional pulsars and housing, 2.5 kg for a separate electronics housing and cabling (ROSINA electronics where integral with the sensor), 1.5 kg for the gas inlet system, and 2 kg for the new detector, its housing and electronics, and the TOF structure.

There are other technical approaches available to achieve the science measurements requirements allocated to the PMS. Some approaches have higher heritage with less performance, and others have less heritage but other technical advantages such as lower mass and power. The AO will solicit instruments based on the science requirements, and the selection board chooses the best balance of performance, cost, and risk. This PMS demonstrates that the science measurements can be obtained within the capabilities of current technology.

4.2.2.4 Sub-Millimeter Sounder

The Sub-millimeter Sounder (SMS) is a passive microwave spectrometer that makes radiance measurements of atmospheric emission lines at very high spectral resolution ($>10^7$) to determine atmospheric composition, temperature, and dynamics. Measurements are made in a tunable (~100 GHz) sub-mm wavelength band. The principal components of the SMS are 1) an articulated (single axis) aperture

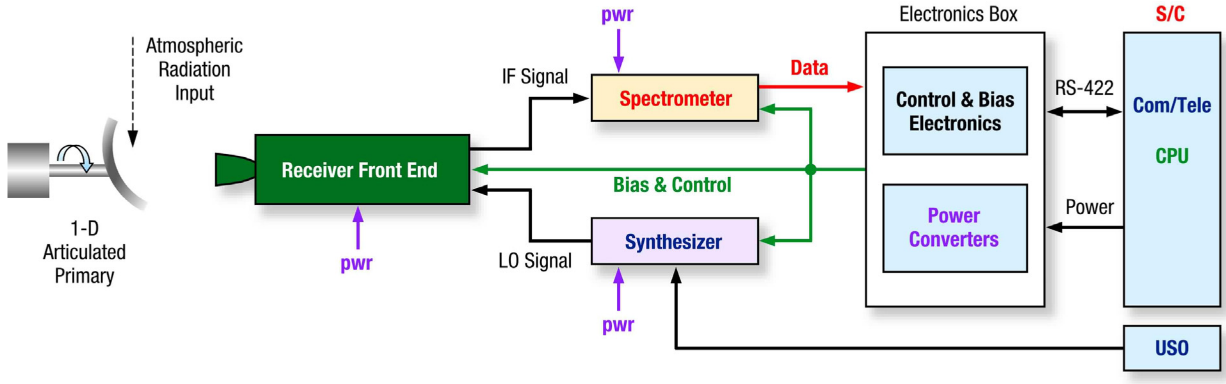


Figure 4.2-8. SMS instrument block diagram.

for collecting the RF signals from the atmosphere, 2) a front-end heterodyne receiver, 3) a back-end processor, and 4) the associated electronics. A block diagram of the SMS is shown in **Figure 4.2-8**. The receiver is tunable and uncooled. The SMS is derived from heritage instruments such as the Microwave Instrument for the Rosetta Orbiter (MIRO) (Gulkis et. al. 2002), the Microwave Limb Sounder (MLS) on Aura (Waters et. al. 1999), the Submillimeter Wave Astronomy Satellite (SWAS) (Melnick et al. 2000), and the sub-mm radiometer on the ODIN spacecraft (Hjalmarson et al. 2003).

The antenna is a 15 cm parabolic dish. It is mounted on a turntable with a bull gear allowing for one-dimensional articulation so that SMS can view both the limb and nadir without requiring spacecraft attitude changes. The 15 cm dish provides a half-power-beam-width (HPBW) of 4 mrad at 600 GHz.

SMS will observe in the limb and nadir directions using the articulated antenna to switch between targets. **Table 4.2-8** contains the performance parameters for SMS. Limb observations will view either normal to the orbit plane in the anti-solar hemisphere or in the orbit plane. The articulation system of the primary antenna will provide in-plane vertical and nadir profiling, and a spacecraft rotation will provide cross-track limb profiling. Slow vertical scanning across the atmosphere at the limb is required. In addition, blank sky and distant celestial targets will be observed for calibration. The integration time required for good SNR is 60 s (per scan step). The output data rate is 14 kbps. Onboard data processing will be performed by the spacecraft computer.

Table 4.2-8. SMS performance.

Parameter	Value
Mass	12.3 kg
Orbit average power	45 W
Frequency range (preliminary)	540–640 GHz
Spectral resolution	300 KHz
Bandwidth	1 GHz
Spatial and vertical resolution (from 3,000 km distance)	12 km
Integration time	1 minute
Sensitivity	1 K in 1 minute; 0.1 K in 1 hour

The SMS electronics are derived from the MIRO electronics. Some of the improvements include a tunable synthesizer and the electronics to articulate the primary antenna. Replacing the MIRO RAD6000 processor with an FPGA-based processor saves both mass and power.

Accommodation Requirements

SMS mass is estimated at 12.3 kg. The volume (exclusive of the antenna) is about 20 × 20 × 20 cm. The average operating power for SMS is 45 W with a standby power level of 10 W. Two hours at the operating power level are required for instrument stabilization when coming from standby before science data can be gathered. SMS requires 28 V DC from the spacecraft. SMS is thermally isolated from the spacecraft. The data interface is standard RS-422.

The mass and power estimates for SMS are based on heritage from MIRO, a deep space heterodyne instrument operating at ~557 GHz. While SMS power estimates are similar to MIRO, the SMS mass is approximately 40% less than MIRO due to 1) single band instead of dual band; and 2) use of a smaller and lighter primary.

Using four times the HPBW, the FOV of the instrument is ~0.9°. Pointing accuracy of 1 mrad with stability of 0.5 mrad over 10 s is required. Nadir and limb viewing in the circular science orbit each require a clear FOV of 20°. The SMS uses signals from the spacecraft USO as a frequency reference in processing its data.

Heritage

The SMS has direct inheritance from the MIRO instrument (**Figure 4.2-9**). It is simplified with a single band versus two and a smaller, lighter antenna. There is only one component on SMS that is under development: a GaN power amplifier that JPL is developing with industry and is scheduled for availability in 1–2 years. Should this not be available, space-qualified GaAs power amplifiers will be used, increasing power consumption by 2 W.

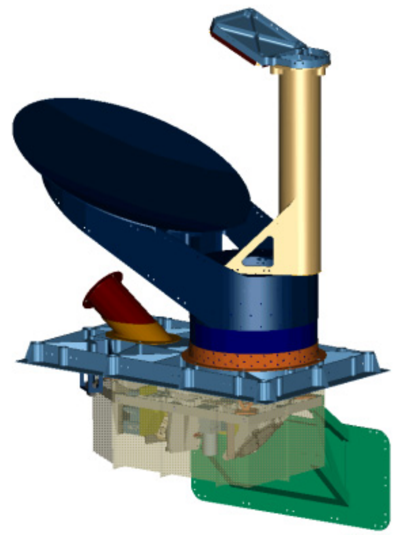


Figure 4.2-9. *The Rosetta MIRO sub-millimeter spectrometer.*

4.2.2.5 Thermal IR Spectrometer

The Thermal IR Spectrometer (TIRS) makes radiance measurements in the range of 30–1400 wavenumbers (7–333 μm) to determine atmospheric temperatures along with atmospheric composition, winds, and surface temperatures. Spectral resolution is achieved using a Fourier transform spectrometer (FTS) and ranges from 0.1 to 15 wavenumbers depending on the scan time used (1 to 120 s). Three different detectors are employed to cover the spectral ranges from 7–9 μm, 9–17 μm, and >17 μm. The two shorter wavelength detectors are HgCdTe arrays of 1x10 pixels; the long wave detector is a 1×4 pixel high critical temperature (Tc) superconductor bolometer array. Spatial resolutions are 3.0 mrad for the HgCdTe arrays and 4.3 mrad for the bolometer. All detectors are cooled to around 80 K using a passive radiator.

Like CIRS (Flasar et. al. 2004), the TIRS opto-mechanical structure is primarily an aluminum alloy. The optics aperture is 25 cm. The telescope is a classical Cassegrain, f/6 overall, with a f/0.7 paraboloidal primary and a hyperboloidal secondary. The design includes a sunshade.

Optics are maintained at about 170 K. A pointing mirror will allow the instrument to view nadir or the limb and will also allow views to space, while an internal shutter provides a warm source for a two-point calibration. TIRS has extensive design heritage from the Cassini Infrared Spectrometer (CIRS) instrument, the Mars Express Planetary Fourier Spectrometer (PFS), and the Mars Global Surveyor Thermal Emission Spectrometer (TES). Signal-to-noise ratios comparable to those achieved by CIRS are expected. A block diagram of TIRS is shown in **Figure 4.2-10**.

The performance of TIRS is shown in **Table 4.2-9**. The raw TIRS science data are interferograms. TIRS science data channels are digitized to 12 bits, and numerically filtered and re-sampled to 16 bits. Loss-less data compression is applied last, taking advantage of the nature of the interferogram signal (large near zero path difference, small elsewhere). A data-compression ratio of 2 or more is typically achieved. The data rate resource of 10 kbps also includes various housekeeping signals, including quality indicators for the science data. In addition, averaging/decimation may be chosen spatially (averaging adjacent pixels, taking every other pixel) or temporally (averaging two successive interferograms, in the process denoted as co-adding) to reduce data rate, if deemed appropriate by the science team or necessary by mission constraints.

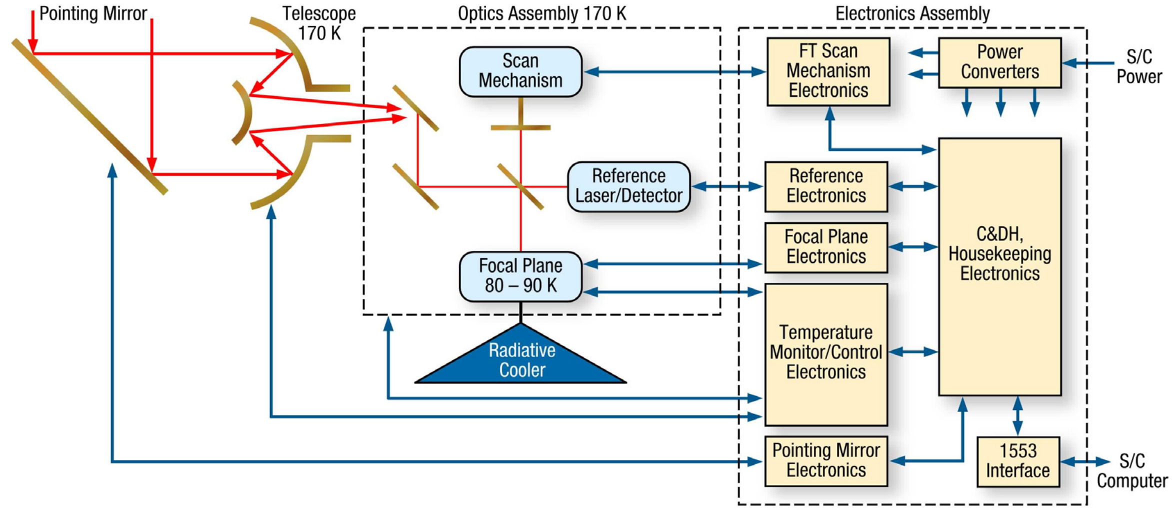


Figure 4.2-10. *TIRS instrument block diagram.*

Table 4.2-9. *TIRS performance estimates.*

Parameter	Value
Mass	16.5 kg
Power	15 W + 2W during pointing
Spectral range	Mid IR (7–16 μm) Far IR (16–333 μm)
Spectral resolution	0.125 to 15 cm^{-1} (120 s to 1 s)
Spatial resolution at nadir	Mid IR: 0.5 km Far IR: 6.5 km
Swath width at nadir	Mid IR: 5 km Far IR: 6.5 km
Integration time	1 to 120 s
Sensitivity (NESR, 1 min integration 3 cm^{-1} resolution) $W/cm^2/sr/cm^{-1}$	Mid IR: 10^{-9} Far IR: 10^{-8} to 10^{-9}
FOV	Mid IR: 3 mrad Far IR: 4.3 mrad

Accommodation Requirements

The volume required by TIRS is estimated at 30 × 40 × 50 cm. The mass is estimated to be 16.5 kg. These estimates are based on scaling arguments from the heritage CIRS instrument, which weighed 43 kg and filled a volume of 76 × 92 × 50 cm, and from a scaled TES pointing mirror. TIRS will combine the two interferometers used by CIRS into a single interferometer by employing a diamond beam splitter. The TIRS primary mirror will have half the diameter of the CIRS primary mirror (25 cm versus 50 cm). Signal-to-noise ratio is maintained in the HgCdTe channels with a larger IFOV. The long-wave channel will maintain the CIRS signal-to-noise ratio by using high Tc bolometers rather than uncooled thermocouple detectors.

The electronics provide power conditioning, housekeeping, command and data handling, motor control for interferometer and pointing mirror scanning, interferometer reference laser and sensor control, temperature control, and focal-plane signal conditioning. The power interface from the spacecraft is 28 V DC. The data interface consists of a 1553 port.

The instrument is thermally isolated from the spacecraft. Cooling is provided by a passive radiator viewing approximately 0.3 sr to dark space. The instrument must be aligned to within 1.0 mrad of nadir and must have a 20° clear FOV in both nadir and limb directions. The detector array lines will be aligned vertically when viewing the atmospheric limb and cross-track when pointed nadir. Pointing stability of <1.0 mrad over a 50 s integration time is required. The average operating power is 17 W, including 2 W for the pointing mirror mechanism. Standby mode power of 10 W is required to maintain thermal equilibrium when not operating. When turned off for an extended period, TIRS must be powered in standby mode for at least one day to restore thermal stability for accurate observations. When standby mode follows an operational period, the delay required for thermal stabilization to resume operations is shortened to 4–6 hr.

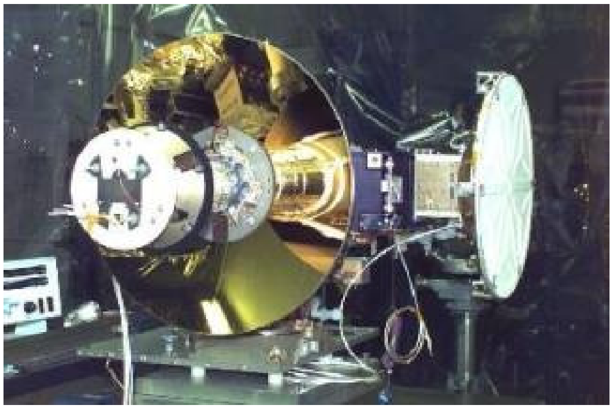


Figure 4.2-11. The CIRS instrument, the basis for the TIRS design.

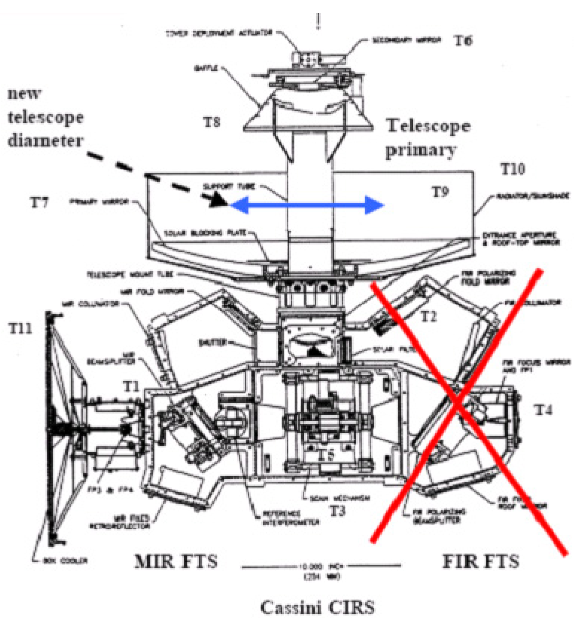


Figure 4.2-12. Configuration changes from the CIRS instrument to TIRS.

Heritage

Extensive flight heritage exists for TIRS from Cassini CIRS (**Figure 4.2-11**). The TIRS optics are similar to CIRS, but scaled downward from a 50 cm primary to a 25 cm primary, enabled in the long-wavelength channel by more sensitive long wavelength detectors (high temperature superconductor bolometers) and in the short-wavelength channel by the closer geometry characteristic of orbiting Titan as opposed to Titan flybys. Further mass/volume reduction comes from replacing the CIRS dual-FTS approach with a single FTS, enabled by having a single beam splitter (synthetic diamond) capable of covering the entire TIRS spectral range (**Figure 4.2-12**). **Table 4.2-10** contains a list of the changes that affect mass and power estimates for TIRS.

Table 4.2-10. Changes from the heritage instrument, CIRS, that affect the estimates for TIRS mass and power.

	Mass deltas	Mass (kg)	Power deltas	Power (W)
Changes from CIRS	Pointing Mirror	1.5	Smaller Volume to Keep Warm	-4.5
	Smaller Aperture	-16.5	Lower Power Electronics (75%)	-4
	Single FTIR Instead of Double	-4.5	dc/dc efficiency - 75% to 80%	-1
	More Compact Electronics (70%)	-4.5	Pointing mirror	2
	Re-design cooler	-1.5		
	Re-design scan mechanism	-0.5		
	Shorter harness	-0.5		
Total Changes		-26.5		-7.5
CIRS		43		25
TIRS Total		**16.5**		**17.5**

TIRS has three recently-developed components, which have all been demonstrated in the laboratory at ambient conditions: synthetic diamond beam splitter, new moving mirror mechanism for the FTS, and the superconducting bolometer detectors. The risk for these developments is low for the beam splitter and the mirror mechanism and moderate for the bolometers. Higher heritage, higher mass components could be substituted if required. A fallback to the CIRS thermopile detectors for the longwave is possible with some loss in sensitivity.

4.2.2.6 Magnetometer and Plasma Package (MAPP)

The Magnetometer and Plasma Package (MAPP) for the Titan orbiter planning payload

Table 4.2-11. *Summary of the capabilities of each MAPP instrument.*

MAPP Instrument	Mass	Power	Range	Resolution	Sensitivity
Plasma	5.0 kg	9.0 W	Ions, e-: 10eV to 30keV 1 to 140 AMU 150 degree cone	$\Delta E/E$ = 0.09 ions = 0.05 elec $M/\Delta M$ = 10 20 x 5 degrees	Elec: $2E^{-4}$ / cm^2 sr Ions: $1E^{-4}$ / cm^2 sr
Energetic Particle Spectrometer	1.5 kg	2.5 W	2 keV / nucleon to 5 MeV 20 to 1000 keV e-	$\Delta E/E$ = 0.2 ions = 0.2 elec $M/\Delta M$ = 10 30 x 15 degrees	Elec: $2E^{-2}$ / cm^2 sr Ions: $1E^{-2}$ / cm^2 sr
Langmuir Probe	1.5 kg	1.0 W	Density: 10 to $1E^6/cm^3$ Temp: 0.1 to 10 eV	1 s	
Magnetometer	2.0 kg	2.5 W	± 50,000 nT	0.05 nT 0.05 s	0.1 nT

consists of four sensors: a dual magnetometer, a Langmuir probe, an energetic particle spectrometer and a wide FOV plasma sensor; **Table 4.2-11** summarizes the capability of each of the MAPP sensors.

This package is planned as a single instrument, having a single science team, a common interface control document (ICD) and command dictionary, and, if prudent, common electronics. For the planning payload, the feasibility of sensor hardware and electronics is demonstrated by using separate existing instruments, whose mass and power are identical to instruments that are already flying and whose combined data rate is 10 kbps. For the Titan orbiter, it is expected that the competitively selected sensors will be packaged so that the accommodation, management, sequencing, science team, and data archiving resource requirements are consistent with that for a single instrument team.

These MAPP sensors are not articulated and do not require a turntable. Instead, the instruments are mounted on the spacecraft so that the various sensors view the highest flux directions of incidence over part of the orbit. For example, the plasma instrument is mounted to have views of both ram directions and the EPS is mounted to preferentially view the zenith direction, the source of higher-energy ions (**Figure 4.2-1b**). Other configurations are possible and are compatible with the spacecraft design.

Each of the four types of sensors that comprise the MAPP suite has extensive flight heritage including several recent missions. The measurement and resource requirements are consistent with these existing instruments, so no development is required for any of the instruments. If necessary, re-packaging requirements can be eliminated and previously-flown instruments can be built with no changes other than those required by changes in existing COTS components.

For the planning payload, only the Langmuir probe shares its electronics. All the other sensors have their own dedicated electronics for commanding and data processing. Each of these instruments is also physically separate and can be optimally located on the spacecraft. This approach preserves the heritage of the instruments: all the mass and power estimates are identical to instruments that are currently flying. All event processing and data compression are performed by the instrument processors; output is formatted as packets and sent to the spacecraft C&DH. The output data rate is 10 kbps.

If necessary to save mass or power, it is possible to package all the MAPP sensors into a common unit. Those savings were unnecessary to demonstrate the feasibility of the planning payload, but they may be useful in the final design of the Titan orbiter.

Plasma Instrument

Plasma instruments have flown successfully for more than 40 years. There are several different technologies with flight heritage, and each one meets both the resource allocation and the performance requirements for the Titan orbiter.

The planning payload uses the PEPE instrument (Young et. al. 2007), which flew on DS1 and is similar the Cassini CAPS instrument. The PEPE instrument, shown in **Figure 4.2-13** and **Figure 4.2-14** uses a tophat energy analyzer which provides a high geometric factor capability. It also has the essential quality of producing various ion fragments in the

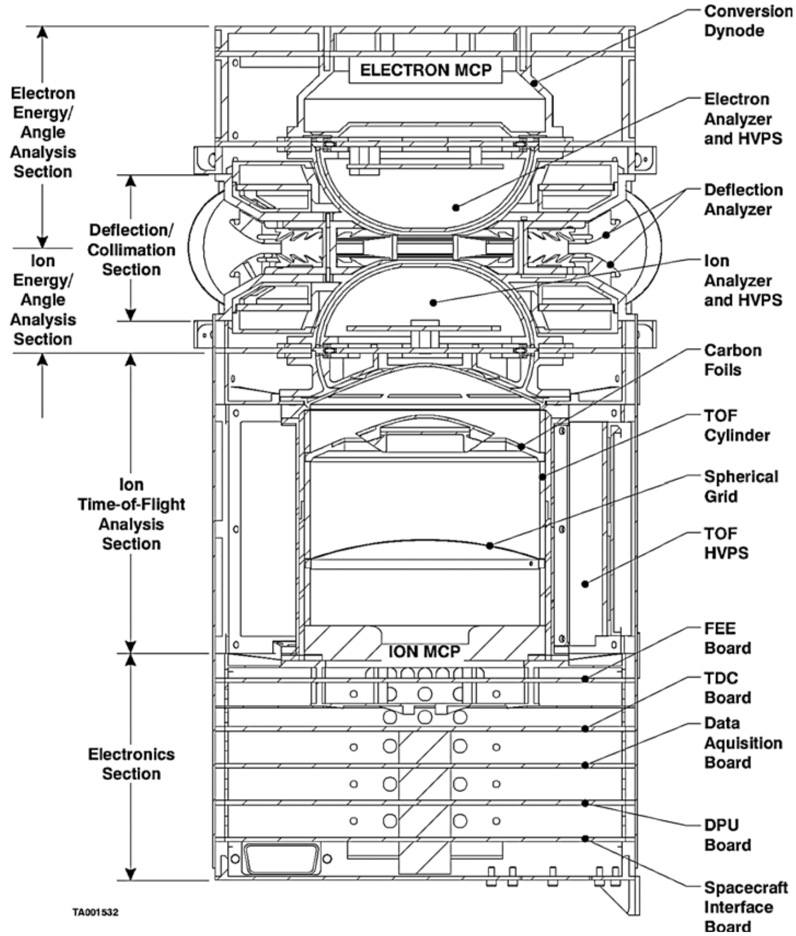


Figure 4.2-13. *Cross section of the PEPE sensor showing major functional components. Ions are analyzed by their energy per charge, two-dimensional position, and total time-of-flight.*

TOF spectrum which will allow one to separate carbon, nitrogen and oxygen based incident atomic and molecular ions (i.e., O^+ vs CH_4^+, OH^+ vs CH_5^+, N_2^+ vs CO^+ vs $HCNH^+$). This technique is similar to that used by neutral mass spectrometers, which use the electron impact ionization technique to produce cracking patterns in the mass spectra, to allow ions of similar mass to be separated. The carbon foil breaks up the molecular species and the LEF electric field separates these ions in TOF.

PEPE detects the plasma ion count rate and velocity vector as well detects ion species. PEPE has a hemispherical FOV of 360 by +/-45 degrees.

PEPE is composed of three major subsystems: a top-hat electrostatic analyzer system, a linear electric field (LEF) time-of-Flight System, and the sensor electronics. The major components of PEPE are shown in **Figure 4.2-13**.

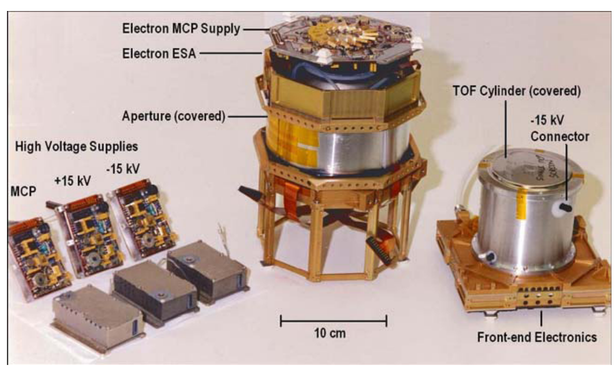


Figure 4.2-14. *The major PEPE subsystems, shown immediately prior to integration on DS1.*

Particles that pass through the ESA have a known E/Q, proportional to the stepped deflection voltage. They are then post-accelerated by

a fixed voltage, before passing through a very thin carbon foil. The exiting ion fragments pass through the LEF electric fields so that neutral and negative fragments are separated in TOF and strike the lower detector (referred to as straight through micro-channel plate (MCP) or ST), while positive fragments strike the top detector called LEF. The mass resolution, when measured in terms of its resolving power in TOF, for the ST detector is M/ΔM ~ 4, while for LEF detector is 20. To first order, the mass-per-charge (M/Q) of a given ion follows from the known E/Q and the measured time of flight, allowing reconstruction of distribution functions for different M/Q species. In the normal scan mode, the ESA system covers the E/Q range in 64 logarithmically-spaced steps every 4 seconds. Using a set of steering lenses, a complete 3-D scan takes 16 s.

Another option for the low-energy plasma instrument is an advanced version of the Cassini Plasma Spectrometer (CAPS) Ion Mass Spectrometer (IMS), which is under development. It is a few kilograms more massive, but has higher mass and energy resolution, and it has mass-spectrometer capability that complements the PMS. A third option is the MESSENGER Fast Imaging Plasma Spectrometer (FIPS) instrument. FIPS mass and power are less than half of PEPE (1.4 kg and 2 W), and its large cone-shaped FOV has some advantages. The AO process will determine the instrument and technology that flies on the final mission.

Since there are several different flight-proven instruments and technologies that can meet the measurement requirements and the allocated resources, the risk for the plasma instrument is very low.

Energetic Particle Spectrometer (EPS)

The second MAPP instrument is a puck-like electron and ion sensor similar to the Juno Energetic-particle Detector Instrument (JEDI) or the Pluto Particle Spectrometer Science Investigation (PEPSSI) (McNutt et. al. 2007) on the New Horizons spacecraft (**Figure 4.2-15** and **Figure 4.2-16**). It measures a few keV to >1 MeV ions and electrons with a nominal fan of 150° × 15° and is a time-of-flight by energy (TOF*x*E) sensor design. The device provides the species, energy spectrum, and angular distribution of the measured particles.

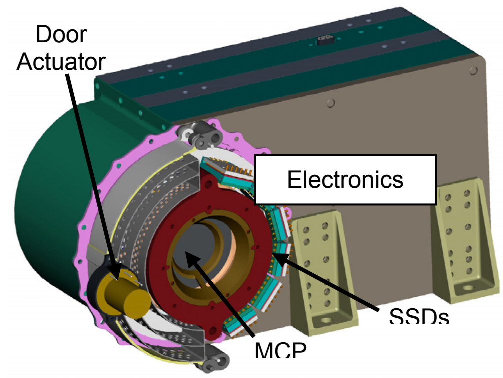


Figure 4.2-15. *CAD cutaway of EPS sensor.*

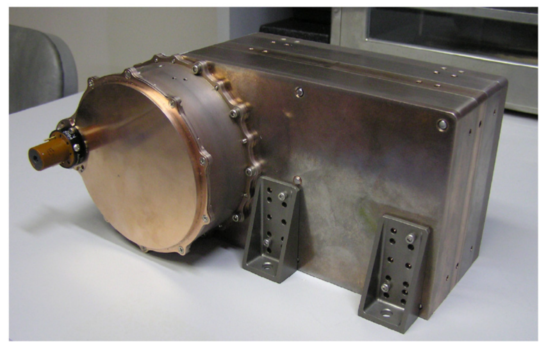


Figure 4.2-16. *Photograph of JEDI EM.*

EPS rejects background by requiring coincidence between the start and stop pulses for the TOF, and the energy signal.

Incoming ion velocities are determined by measuring the time-of-flight (TOF) between two thin foils (**Figure 4.2-17**). The EPS uses a TOF ASIC chip to measure the start/stop time difference with 1.0 ns resolution.

The ion energy is determined by measuring the energy deposited in one of twelve 700 μm thick solid state detectors (SSDs), six of which are active at a time. Detectors in one group of 6 are 20 times smaller than the other, enabling variations in the geometry factor for E *x* TOF coincidence events. The ion species are determined using the measured energy and velocity. Ions not striking an SSD, below the SSD threshold (~20 keV), are categorized by using the pulse height measured from MCP output.

Electrons are measured in the SSDs that are covered by 2 μm thick layers of aluminum flashing. This aluminum stops ions with energies up to 200 keV before they reach the detectors, whereas electrons reach the detector

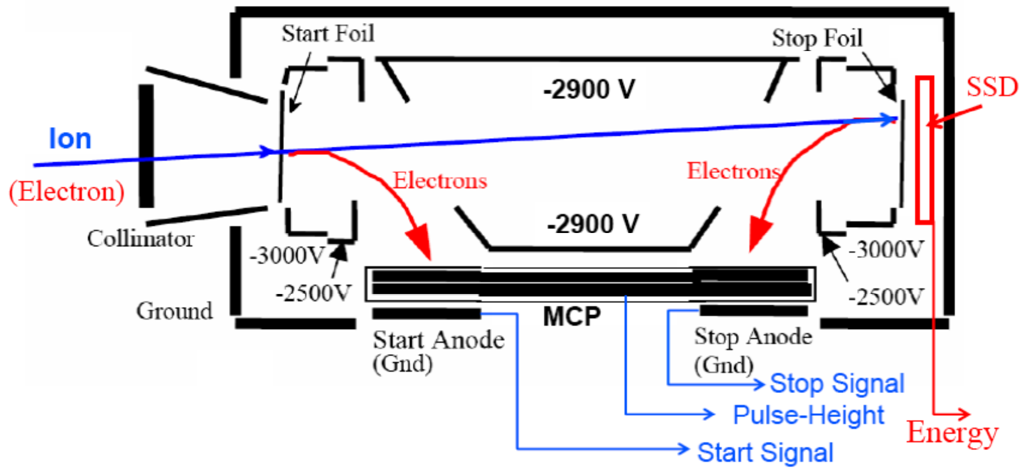


Figure 4.2-17. EPS TOFxE schematic.

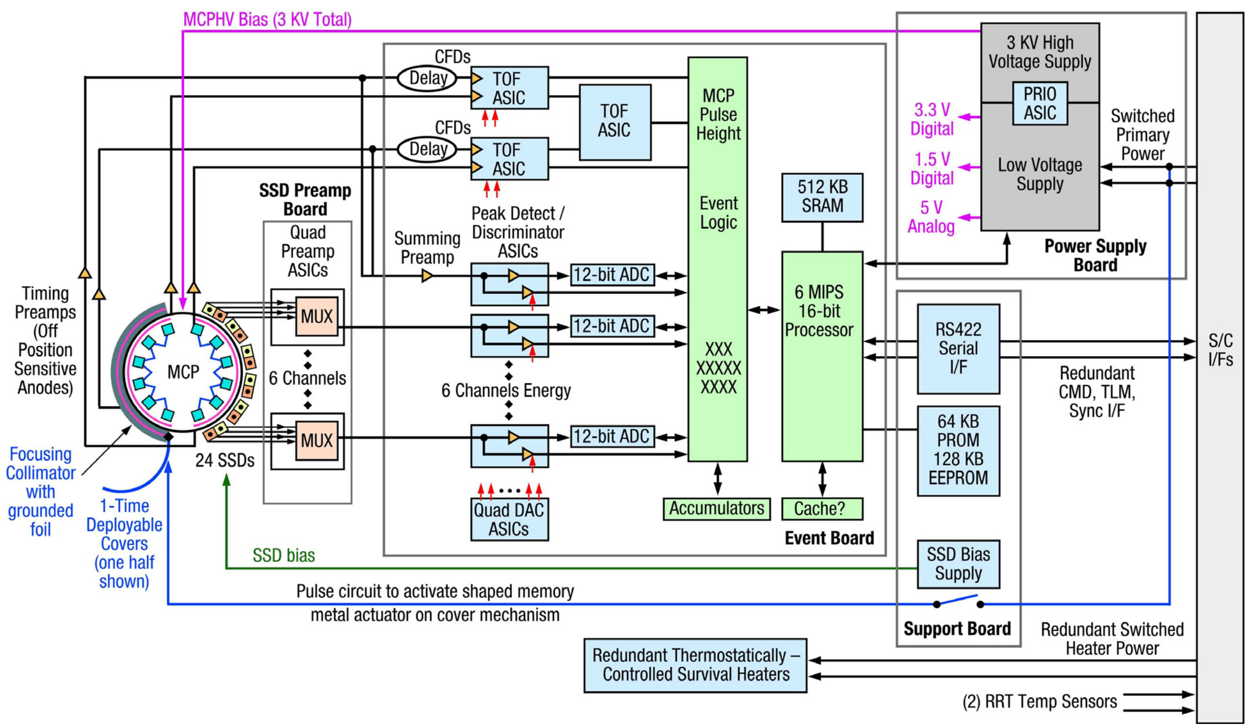


Figure 4.2-18. EPS block diagram.

through the flashing, losing only a few keV. The difference between the flashed and unflashed SSD responses further serves to discriminate between ions and electrons.

Background rejection for ions on EPS relies on valid event logic that requires coincidence among three separate detector signals.

An instrument-controlled, one-time deployable door, identical in design to that used on New Horizons/PEPSSI, protects the sensor's thin foils from acoustic energy during launch.

As shown in the EPS block diagram, **Figure 4.2-18**, the EPS sensor contains its own preamplifier/shaper circuits to amplify the SSD signals with 500 ns shaping and fast baseline restoration for high rate performance. The amplified signals feed peak detector/discriminator ASICs, capturing the peak amplitude of the signals and generating triggers to the digital Field Programmable

Gate Array (FPGA)-based event circuitry. The logic categorizes the event and increments appropriate 24 bit counters, then resets the analog channels. The event processors can each handle more than 2.5×10^5 sensor events per second (and detector rates >1 MHz).

Sensor event collection and analysis, command and telemetry processing, and instrument control and monitoring functions are carried out by the instrument processor, implemented on an FPGA. Most data are losslessly compressed prior to packetization; compression factors of >1.66 have been achieved in similar recent missions.

Magnetometer

A fluxgate magnetometer similar to those flown on several other missions, including MESSENGER (one 3-axis magnetometer, Anderson et. al. 2007) and Galileo (two magnetometers). It comprises two DC magnetic sensors mounted on a 3.6-m boom, one at the tip and the other about half way out from the spacecraft. Fluxgate instruments rely on the hysteresis effect found in ferromagnets. Two solenoids with ferromagnetic cores wound in opposite directions are driven with a sufficiently high frequency (several kHz) current to drive them into saturation. The difference field between these coils is sensed by a third coil, which sees a second harmonic of the primary field. This second harmonic field is rectified and smoothed and is directly proportional to the background field. The rectified field is exceptionally linear and is digitized using A/D converters. A block diagram of the MAG is shown in **Figure 4.2-19**.

The highest cadence rate required is 32 vectors/s to measure the wave activity near Titan. The expected field range over the whole mission is 0–1000 nT. The spacecraft will be designed for magnetic cleanliness. The magnetic field of the spacecraft at 3.6 m distance along the boom must be <0.05 nT for oscillations with periods between 1 s and 15 minutes. Fields with oscillations outside this range, including DC fields, can be as large as 1 nT. The strongest spacecraft magnetic field emitter, the ASRG, has a frequency of 100 Hz and an amplitude significantly below 1 nT. The two sensors provide additional capability to detect and subtract spacecraft fields that vary at the detection level of the sensors.

The sensor is mounted at the end of the boom and has no active electronics. The magnetometer electronics will be housed in the science electronics chassis. The baseline MAG is capable of data processing and requires two electronic cards. It incorporates a CPU and internal RAM memory (<2 Mbytes) for data processing and burst mode. The baseline instrument can manage I/O and data processing

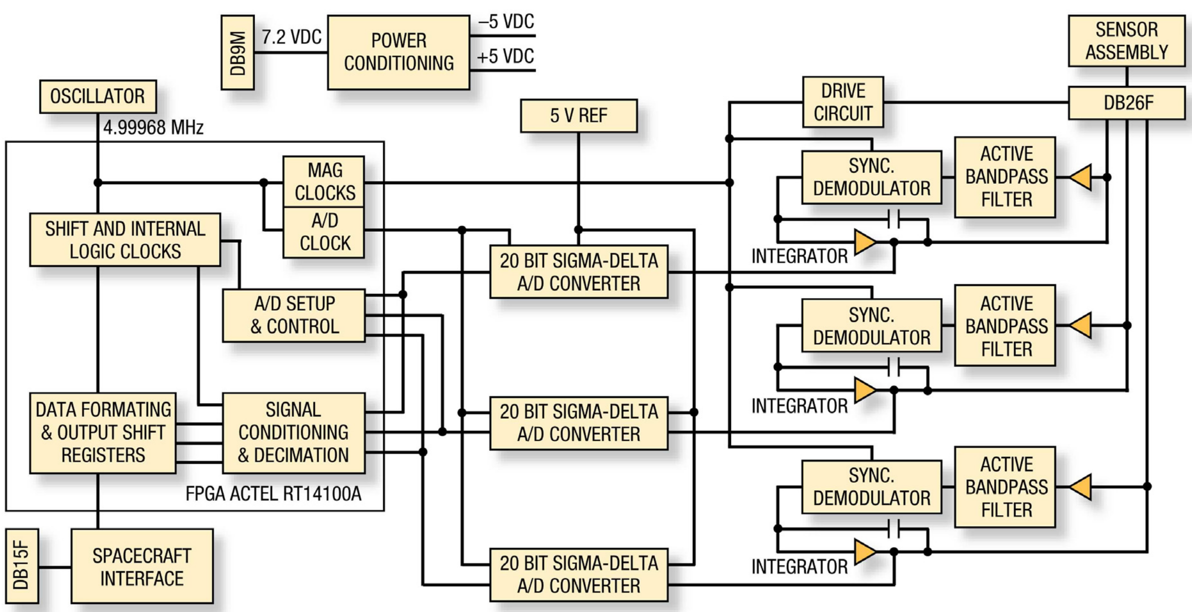


Figure 4.2-19. *Magnetometer block diagram.*

and limited storage (to avoid blackouts at critical times). The output data rate is 2 kbps per sensor (uncompressed).

The dual magnetometer design reduces two types of risks. First, the dual magnetometer is able to quantify and therefore separate the internal field from the spacecraft from the background field. Secondly, if one magnetometer were to fail, the second one would still be able to fulfill the science role if calibrations are performed in space to assess the spacecraft generated magnetic field.

The fluxgate sensors suffer from small but measurable drifts in their zero levels. On a non-spinning spacecraft such as for TO, these can be measured in the solar wind by utilizing the rotational nature of the interplanetary magnetic field. Calibrations from the measured field will need to be performed once a week. Continuous data at a resolution of 1 s or better is required. Once inside Saturn's magnetosphere, in the Saturn Tour Phase, slow spacecraft spins around two orthogonal axes will be required to determine offsets. These are performed roughly once every week. In the primary Titan Science phase, spacecraft spins around the two orthogonal axes are performed once every month.

As stated in §4.2.1.1, the ASRG residual magnetic AC field is less than the required sensitivity of the magnetometer at the end of the boom. A spacecraft magnetics control program will ensure that other subsystems have minimal effect on magnetometer science. Features of successful programs include screening all spacecraft components that have magnets or magnetic materials; avoiding current loops in the design of the battery, power distribution system, and spacecraft harness; applying point shielding; and demagnetizing hardware. Anderson et al. 2007, contains addition descriptions of flight-proven magnetic cleanliness techniques, particularly for the three spacecraft systems that have the potential to generate the largest magnetic signatures: propulsion latch valves, RWA, and the battery.

The Titan magnetometer has similarities to instruments flown on Galileo, Polar, Fedsat, MESSENGER, and Space Technology 5 (ST5). The mass estimate for the Titan planning payload is based on the MESSENGER MAG instrument as shown in **Table 4.2-12**. The two additional electronics boards are a second drive board and second A/D board. The power estimate, which includes heaters to keep the sensor temperature stable, is 3.0 W, up from 2.5 W for the MESSENGER magnetometer. This includes the second sensor and assumes some improvement from higher-efficiency DC/DC convertors.

Table 4.2-12. *Derivation of magnetometer mass from the MESSENGER magnetometer: MAG.*

Item	MAG	Titan
Sensor	184g	390g (2nd Sensor)
Electronics	835g	1,250 (2 additional boards)
Cable	408g	600g (2nd, short cable)
Boom	2.66 kg	2.66 kg
Total (w/o boom)	**1.4 kg**	**2.2 kg**

Langmuir Probe

A Langmuir probe on the orbiter provides, with minimal resources, a very reliable *in situ* measurement of electron density and temperature as well as some ion diagnostics, given either a measured or modeled composition. Further, this instrument does not rely on the long antennas required by an ionospheric sounder, and hence would be available for orbits in which the periapsis dips well below 1000 km. A Langmuir probe measures current as a function of the voltage applied to the probe to determine the number density of electrons and their temperature in the positive (electron collecting) portion of the current–voltage sweep. In fact, detailed modeling of the sweep can distinguish between photoelectrons and ionospheric electrons and can provide information on the spacecraft potential (important for the interpretation of plasma measurements by a plasma instrument) and even UV input, also important to the interpretation of the ionosphere. In the negative (ion collecting) portion of the current–voltage curve, some information on the ion speed (a combination of thermal motion and bulk motion) is available, provided there is some information on the characteristic mass of the ions, available either from other onboard measurements or from models.

The Langmuir probe, much like that flying on Cassini, would likely be operated in a mode with periodic voltage sweeps, on the order of

once per second, with rapid (tens of milliseconds) fixed-voltage current measurements in between to provide high-resolution density measurements between the sweeps. The basic measurements are electron density and temperature, ion speed (or temperature), UV flux (modeled), and spacecraft potential.

4.2.2.7 Radio Science and Accelerometer

The planning payload includes provision of a dual-frequency transponder in the spacecraft telecommunications system, providing 2-way coherent Doppler tracking and range measurements required for orbit reconstruction in support of geophysical modeling and navigation. The transponder has X-band and Ka-band for both uplink and downlink, in order to provide the highest-quality data. Noise in the Doppler measurements is dominated by line-of-sight plasma effects in the solar wind and the Earth's ionosphere. Having dual links (X- and Ka-band) for both uplink and downlink enables the optimum plasma calibration, yielding improvement over the approximate 0.03 mm/s (30 s integration time) provided by single-frequency X-band tracking.

As on Cassini, there are formidable results to be obtained from radio science techniques. As with many of the orbiter investigations, the ~2 orders of magnitude enhancement in observation opportunities vastly improves the science capability. The polar orbit will significantly improve the determination of tidal changes in Titan's gravity field, which will be determined up to order ~6 via tracking.

The gravity science branch of radio science will utilize the dual-frequency transponder in a 2-way coherent mode, taking advantage of the high stability of the uplink signal referenced to the hydrogen-maser-based clock at DSN stations. Gravity data are collected whenever the spacecraft antenna is pointed to Earth and sufficient power is available for the operations of the dual-links as well as during periods dedicated to gravity science as negotiated within the science team for specific target areas. Spacecraft accelerometer data supplements the Doppler tracking for orbit reconstruction. The required accelerometer noise performance is less than 10^{-11} m/s^2 rms over one day. Note that gravity science is enhanced by synergy with the altitude information obtained by the TiPRA.

Radio occultation science, which uses the transponder in one-way mode, will be performed at intervals throughout the mission, yielding path-integrated ionospheric electron density profiles, and stratospheric and tropospheric temperature profiles at a range of latitudes during the Circular Orbit Phase. Occultation science takes advantage of the stability of the on-board USO, which must have an Allan Deviation of 10^{-13} at an integration time of 10 seconds. The radio occultation technique for atmospheric investigation is constrained by the quality of the USO, the received signal-to-noise ratio and accurate pointing on both the spacecraft and at the Deep Space Network. One-way measurements are required for occultations because on occultation egress, the transponder will not lock-up to the uplink in a timely fashion, thus missing the atmosphere. Atmospheric occultations have been carried out on numerous missions including Cassini at Saturn and Titan yielding significant results in the atmospheric structure via temperature-pressure profiles. This technique is key to achieving the science objective "characterize the atmospheric and flow energy over seasonal and longer timescales," and the science investigation "determine the atmospheric thermal and dynamic state."

Accommodation Requirements

The radio system hardware elements, including the Universal Space Transponder with a Ka stability of 10^{-15} at 1000 seconds, an ultra-stable oscillator (USO), and tri-axial accelerometers (a component of the attitude control system), are described in §4.4.3.4 and §4.4.3.6. Unlike other on-board instruments, radio science instrumentation typically does not perform any data processing on-board the spacecraft and has no requirements for flight software.

Heritage All radio science techniques are proven and have been utilized on many other missions. The USO design has very high flight heritage on numerous missions. The transponder performance is typical of previous requirements that have been met on many missions for X-band and Cassini for X- and Ka-bands (and accepted for Juno which is in the development phase). Although the Universal Space Transponder (UST) is under development, it is not based on new technology. It is

an engineering development based on proven technologies with flight heritage such as the Electra Payload on previous deep space missions.

4.3 Mission Design Overview

This section discusses the TSSM Baseline mission design. Other mission design options have been examined and are discussed in §3.0 of this report. The trajectory described in this section was designed with numeric simulations using models detailed in §4.3.12.

For the Baseline design, the NASA orbiter with both of the ESA provided *in situ* elements are launched together in September 2020 on an Atlas V 551 from Cape Canaveral. The Flight System then performs a nine-year interplanetary trajectory with solar electric propulsion in combination with gravity-assists of Venus and Earth to reach Saturn in October 2029.

After a 746 m/s Saturn Orbit Insertion (SOI), the orbiter begins a two-year Saturn Tour Phase with 16 Titan and 7 Enceladus flybys. An ESA-provided RPS-powered montgolfière is delivered on the first Titan flyby, and an ESA-provided battery-powered lander is delivered on the second Titan flyby.

After the two-year Saturn tour, the orbiter enters Titan orbit with a 388 m/s Titan Orbit Insertion (TOI) maneuver on September 29, 2031. The 22-month Titan Orbit Phase begins with a 2-month Aerobraking Phase. Over these 2 months, the apoapsis altitude is reduced from 15,000 km to 1500 km via Titan aerobraking passes. The orbit is then circularized to a 1500 km, near-polar (85°) mapping orbit. This orbit begins with an descending node at a Local Solar Time (LST) of 11:30 am, which progresses to 9:00 am by the end of the 20-month Circular Orbit Phase.

At the end of the mission, a small de-orbit burn places the spacecraft on an orbit that will decay and impact Titan by the end of the 6-month Decommissioning and Disposal Phase. This decaying orbit is controlled and the final impact point of the spacecraft can be deflected away from regions several hundred kilometers across. This will enable the mission to avoid any regions of planetary protection concern where the possibility of near-surface water may have been identified during the mission. (see §4.7 for details of TSSM's planetary protection approach.)

4.3.1 Mission Phase Definitions

The mission timeline is detailed on **Foldout 1** (**FO-1**) with mission phases and sub-phases defined and detailed in **Table 4.3-1**. These phase names are used throughout this report.

4.3.2 Launch

The spacecraft would begin its journey on an Atlas V 551 rocket launched from Cape Canaveral. **Table 4.3-2** details the prime launch opportunity in 2020 (the backup opportunities are detailed in §4.3.11 of this report). There is virtually no change in performance over the 21-day launch period required by the study ground-rules. The launch C_3 doesn't change enough to get different launch masses from the KSC ELV performance website, hence the identical launch masses. This robustness is due to the use of a Solar Electric Propulsion (SEP) stage that results in greater flexibility in the interplanetary trajectory compared to traditional gravity-assist trajectories. Moreover, the use of SEP enables the launch period to be extended well beyond the 21 days shown for no additional mass penalty.

4.3.3 Interplanetary Trajectory

Figure 4.3-1 shows the SEP trajectory used to reach Saturn. **Table 4.3-3** details the flybys and other major events during the interplanetary cruise from launch to Saturn arrival. The SEP thrusting and gravity-assist flybys occur during the solar electric cruise, which lasts for 5 years after launch. At the end of the SEP thrusting, the SEP stage will be released such that it will impact Saturn (for planetary protection). The next 3.3 years is a ballistic cruise with no flybys or SEP thrusting. Six months prior to Saturn arrival, activity increases to prepare for SOI and begin taking optical navigation images to support Enceladus flybys.

Table 4.3-4 lists the design assumptions used for the low-thrust trajectory design. These assumptions are intended to give margin to the design and allow for future design refinements such as robustness to periods of missed thrust and implementation of targeting strategies for the Earth flybys. The values in this table result from a study conducted at JPL of appropriate margins for SEP missions (Oh et al. 2008). A principal difference from the recommendations of the JPL SEP margins study is shorter forced coast periods around flybys and the use of 3%

Table 4.3-1. Mission phase definition and description.

Phase	Activity	Duration
Interplanetary Cruise (9 years)	Launch and Early Operations: Launch from CCAFS and activities, including initial acquisition by the DSN, checkout and deployment of all critical spacecraft systems and preparations to begin thrusting with the Ion Propulsion System (IPS).	2 months
	Solar-Electric Cruise: Thrusting with the IPS and gravity-assist flybys of Earth and Venus. Several activities associated with flybys, thrust arc design, and Earth avoidance.	5.0 years
	Ballistic Cruise: Once the SEP stage is jettisoned, the spacecraft enters a period of low activity.	3.3 years
	Saturn Approach: Preparations and readiness testing for Saturn Orbit Insertion (SOI). Optical navigation for upcoming Enceladus flybys.	6 months
Saturn Tour (2 years)	Saturn Arrival: SOI performed between Cassini-like ring plane crossing in the F–G gap	2 years
	ISE Delivery: Starts with 214 d period orbit with a Balloon Targeting Maneuver (BTM) to target to the montgolfière entry position and velocity, release of the montgolfière, and a Periapsis Raise Maneuver (PRM) to target the first Titan flyby. On the following orbit, a Lander Targeting Maneuver (LTM), Lander Release, and Orbiter Deflection Maneuver (ODM) deliver the Lander to Kraken Mare.	
	Enceladus Flybys: Seven close (100–500 km) flybys of Enceladus allowing *in situ* measurements of the plume and remote sensing of active region. Additional opportunistic flybys of other icy moons possible, such as Rhea in the example tour.	
	Final Energy Reduction: Series of orbits with large maneuvers to lower Titan V_∞ to ~940 m/s prior to Titan orbit insertion. Moderate-sized maneuver sets up proper initial orbit plane geometry.	
Titan Orbit (1.9 year)	Aerobraking: Starting from an 720 km by 15,000 km orbit, Titan aerobraking is used to help circularize orbit and provide deep sampling of Titan atmosphere to 600 km.	2 months
	Circular Orbit: Detailed surface mapping of Titan from a 1500 km, circular, polar (85°) orbit that starts with and a decending node at 11:30 am LST and reaches 9:00 am by the end of the mission.	20 months
Decommissioning and Disposal	At end of prime mission, a ~15 m/s maneuver places spacecraft in an orbit that will decay in < 6 months. During this phase small maneuvers will be used to keep the final entry point away from any regions of concern for planetary protection.	6 months
Extended Mission	Minimal orbit maintenance requirements mean that the spacecraft could continue in Titan orbit for an extended mission of several years as allowed by funding and spacecraft health.	

Table 4.3-2. 21-day launch period for 2020 opportunity.

	Beginning of Launch Period	Middle of Launch Period	End of Launch Period
Date	Sep 10	Sep 19	Sep 30
C_3 (km^2/s^2)	0.60	0.64	0.64
DLA (deg)	-19.5°	-20.5°	-21.2°
Launch Mass (kg)	6265	6265	6265
SEP ΔV (km/s)	2.63	2.68	2.77
Xenon Fuel (kg)	390	397	410

Table 4.3-3. Interplanetary events.

Event	Date / Altitude
Launch	Sep 10–30, 2020
Start SEP Thrusting	Dec 1, 2020
Earth-1	Oct 27, 2021 / 16,900 km
Venus	Feb 4, 2022 / 5300 km
Earth-2	Jun 11, 2023 / 4500 km
Earth-3	Jun 11, 2025 / 600 km
End SEP Thrusting	Oct 14, 2025
SOI	Oct 28, 2029

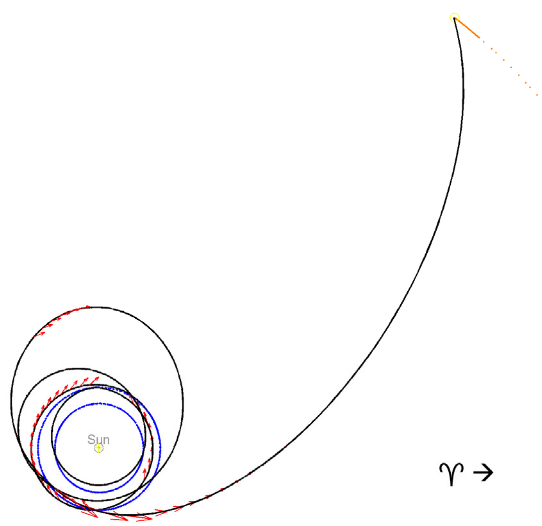


Figure 4.3-1. 2020 EVEE SEP trajectory with arrows showing thrust periods and directions.

FOLDOUT 1
BASELINE MISSION DESIGN

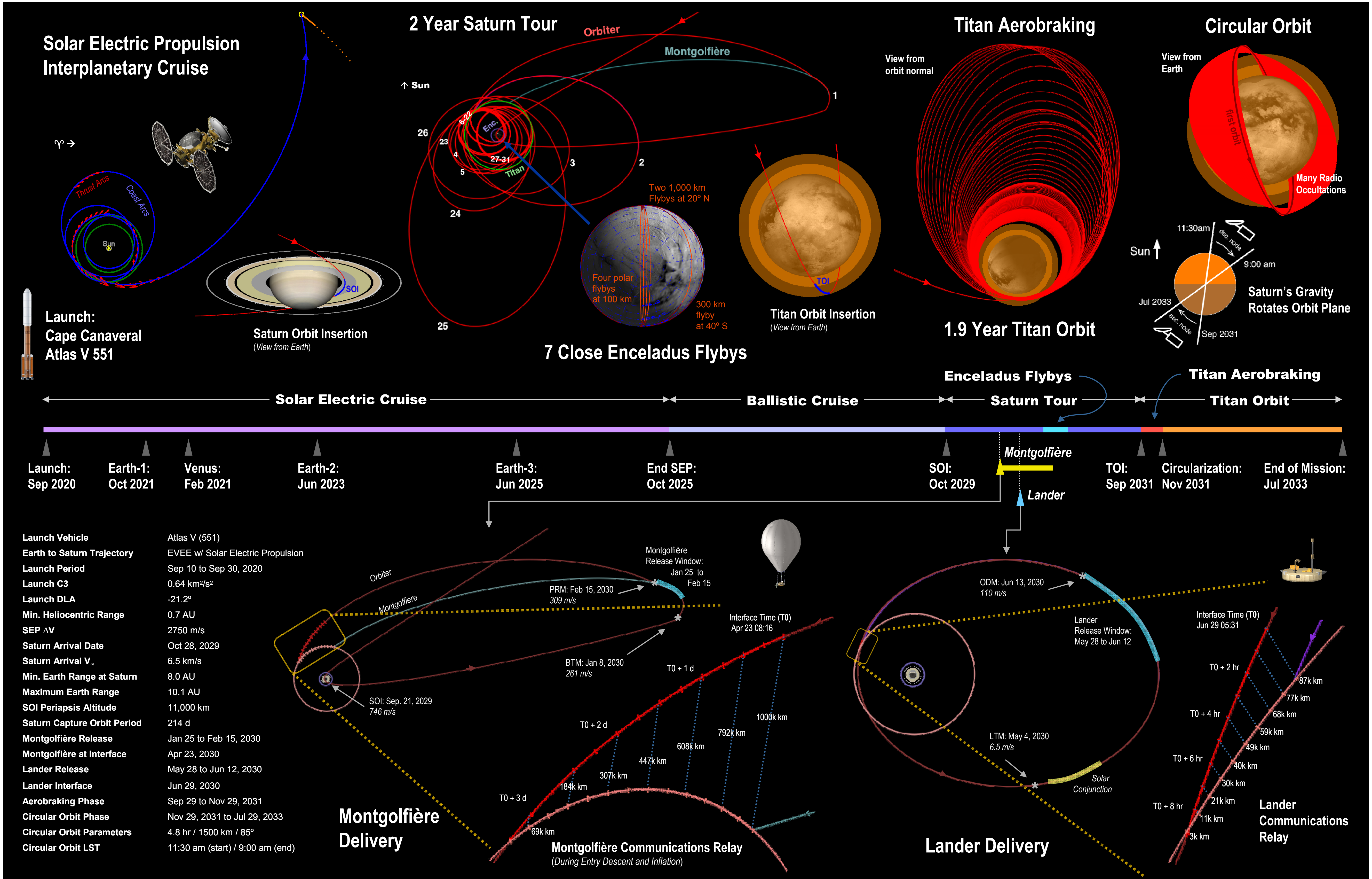


Table 4.3-4. SEP trajectory constraints.

Parameter	Value	Rationale
Flight-System Power Margin	5%	Arrays are sized to provide 15kW after accounting for a 5% margin on total system power
Trajectory Power Margin	5%	Reduced power protects against heliocentric range variations across operational contingencies
Propellant Margin	10%	Provides robustness to engine performance changes
Planned Thrust Outages	3%	Period of planned thrust arcs lost to downtime for spacecraft maintenance tasks, solar conjunction, etc.
Unplanned Thrust Outages	5%	Robustness to unplanned thrust outages
Forced Coast after Launch	60 d	Two months for initial checkout of spacecraft and Ion Propulsion System (IPS)
Coast during Flybys	+/- 1 d	Coast period to avoid any problems with solar eclipse and for thermal control during Venus flyby
Minimum Flyby Altitude	400 km	Assumes a minimum operational Earth flyby altitude of 300 km (based on Galileo studies) with 33% margin for robustness to missed thrust.

for planned thrust outages as opposed to the 5% recommended by the study. This is because TSSM does not have planned thrust outages for radiometric tracking or long tracking periods around flybys. This is possible because the Flight System design can accommodate radiometric tracking during thrust periods as a result of the articulating high gain antenna and accelerometers (10 nano-g) sensitive to <1% of the ion thrust magnitude.

The SEP trajectory allows sending more mass to Saturn than chemical trajectories. This is principally due to the addition of a 1-year Earth-to-Earth leg after launch that substantially reduces the launch C_3 needed from 11–19 km^2/s^2 for chemical in the 2018–2022 launch years to only 0.6–1.4 km^2/s^2.

For the types of SEP trajectories examined in the past, the mass of the SEP stage (778 kg, including margin) offset much or all of this mass advantage. However, this study has developed and applied powerful new methods for finding SEP trajectories that make use of inner solar system gravity assists to provide superior performance. Once found, these trajectories were developed and validated using proven methods (see §4.3.12).

The SEP trajectory also adds substantial robustness across many potential risks. These trajectories provide the ability to dial-in a flight time for a wide range of masses. This offers an unprecedented and exciting degree of flexibility and robustness for an outer planets mission. Details on how alternate SEP trajectories with longer times of flight can deliver more mass to Saturn if needed, and conversely how shorter flight time trajectories are possible if the Flight System mass is reduced can be found in §5.0.

This design currently uses three high performance NEXT ion engines (up to two thrusting with one as a spare). In addition, §5.0 shows alternate trajectory options using lower performance BPT-4000 Hall thrusters or XIPS ion engines that deliver the full Baseline Flight System mass for only a slightly longer flight-time. Alternative chemical trajectories are also discussed in §5.0 that can deliver enough mass for a mission without the SEP stage, although with a larger flight-time penalty.

4.3.4 Saturn Tour Trajectory

This phase begins with Saturn Orbit Insertion (SOI). On either side of SOI, the spacecraft crosses through the same gap between the F and G rings used by Cassini. During these crossings, like Cassini, the High Gain Antenna (HGA) will be put in the ram direction and used as a dust shield. Cassini has given us a much better understanding of the debris environment near the rings and TSSM can pass closer to the F-ring than Cassini did. This saves propellant and gives opportunities for spectacular observations of the rings. In addition, Cassini's observations of the D-ring have opened up an exciting possibility of a passage between the D-ring and Saturn that will be examined during Phase A for possible additional ΔV savings. As shown on **FO-1**, the entire burn is visible to Earth and can be monitored via the spacecraft's low gain antenna (LGA).

The 2-year gravity-assist tour is required to deliver the montgolfière and lander (see §4.3.5), provide flybys of Enceladus with *in situ* sampling of its plume, and to reduce the orbiter energy prior to TOI for efficient capture at Titan. This tour is designed to the constraints given in **Table 4.3-5**. The minimum flyby altitude given in this table is a function of flyby v-infinity due to atmospheric heating. For the Aerobraking Phase, the spacecraft is designed to tolerate atmospheric heating of up to 0.25 W/cm^2. **Table 4.3-6** gives the flyby

Table 4.3-5. Tour design constraints.

Parameter	Value	Description
Duration	2 yr	Duration balances Saturn tour science with Titan orbit science.
Enceladus Flybys	4+	Must achieve at least 4 close flybys over Enceladus South pole.
Minimum Titan Altitude for Vinf < 3 km/s	800 km	Accounts for spacecraft heating limits with margin for navigational accuracy. First low Titan flyby is limited to 900 km to confirm atmospheric model.
Minimum Titan Alttitue for Vinf < 2 km/s	750 km	Accounts for spacecraft heating limits with margin for navigational accuracy.
Minimum Titan Altitude for Vinf < 1 km/s	720 km	Accounts for spacecraft heating limits with margin for navigational accuracy.
Minimum Enceladus Flyby Altitude	100 km	Leaves margin for navigational uncertainty. This may likely be lowered to 50 km or even 25 km after more detailed analysis.
Minimum time between low altitude flybys	8 d	Close flybys must be separated by at least 8 days to allow sufficient time for maneuvers. Distant flybys may be closer if targeted as a Cassini-style double flyby.
Solar Conjunction	Avoid Conjunction	Tour maneuvers and flybys placed with consideration of Ka-band limits of > 3° SEP for commanding and telemetry, and > 7° SEP for radiometric tracking.

Table 4.3-6. Titan flyby heating limits.

Flyby V-Infinity	0.25 W/cm^2 Heating Altitude
3 km/s	720 km
2 km/s	680 km
1 km/s	650 km

altitudes where that heating is achieved using the atmospheric models described in §4.3.7. The minimum altitudes in **Table 4.3-5** are above these values to give additional margin for navigation performance.

A two-year tour is detailed in **Table 4.3-7** and depicted in **Figure 4.3-2**. This tour is part of a fully integrated, end-to-end trajectory from launch to spacecraft disposal used to confirm the feasibility of the TSSM mission design and to generate an accurate ΔV budget. It is point-design representative of a much larger space of possible tours. Starting in Phase A and continuing through Phase E, a tour design effort will be undertaken to optimize the TSSM tour for Science to the level of the Cassini extended mission design. It is reasonable to expect that such an effort will lead to

Table 4.3-7. Saturn tour design showing flyby altitude and v-infinity along with post-flyby Saturn orbit inclination and period.

	Body	Date	Alt [km]	Vinf [km/s]	Per [d]	Inc [deg]
SOI	Saturn	28-Oct-29	11236	6.6	214.0	5.7
Ti1	Titan	26-Apr-30	1000	2.8	91.3	17.2
Ti2	Titan	29-Jun-30	1200	2.7	45.6	24.1
Ti3	Titan	31-Jul-30	900	2.7	22.9	26.6
Ti4	Titan	16-Aug-30	1077	2.7	22.9	19.3
Ti5	Titan	1-Sep-30	800	2.7	22.8	5.3
Ti6	Titan	17-Sep-30	2331	2.7	15.1	0.6
Rh1	Rhea	5-Oct-30	1273	3.6	15.5	0.5
Ti7	Titan	18-Oct-30	1817	2.8	11.4	0.5
Ti8	Titan	3-Nov-30	1241	2.8	10.0	0.5
En1	Enceladus	7-Nov-30	1000	7.1	9.8	0.5
En2	Enceladus	14-Nov-30	100	7.1	9.8	0.5
En3	Enceladus	21-Nov-30	100	7.2	9.8	0.5
En4	Enceladus	28-Nov-30	307	7.1	9.8	0.5
En5	Enceladus	5-Dec-30	100	7.1	9.8	0.5
En6	Enceladus	11-Dec-30	100	7.1	9.8	0.5
En7	Enceladus	18-Dec-30	1110	7.2	9.8	0.5
Ti9	Titan	21-Dec-30	2128	2.8	11.4	4.8
Ti10	Titan	6-Jan-31	2687	2.8	15.2	4.8
Ti11	Titan	7-Feb-31	3460	2.8	22.9	3.8
Ti12	Titan	23-Feb-31	2717	2.8	45.7	1.5
Ti13	Titan	27-Mar-31	3477	2.8	133.9	0.5
Ti14	Titan	29-Jun-31	750	1.7	43.4	0.3
Ti15	Titan	28-Jul-31	720	0.96	22.9	5.1
Ti16	Titan	13-Aug-31	2570	0.95	17.2	7.9
TOI	Titan	29-Sep-31	760	0.94		

significant improvement over what is already an exciting tour design.

A primary focus of the Saturn tour design is the Enceladus flybys, which are optimized to make best use of TSSM instrumentation that is greatly enhanced relative to that carried by Cassini. These flybys currently target the active region at the Enceladus south pole (see **FO-1**). However, it is possible to retarget these encounters in-flight if the active region changes at the time of the TSSM mission. Such a change in activity can be determined from distant observation of Enceladus prior to the close flyby phase.

Although Enceladus is a key driver of the tour design, the rich cadre of icy moons at Saturn will provide many fortuitous opportuni-

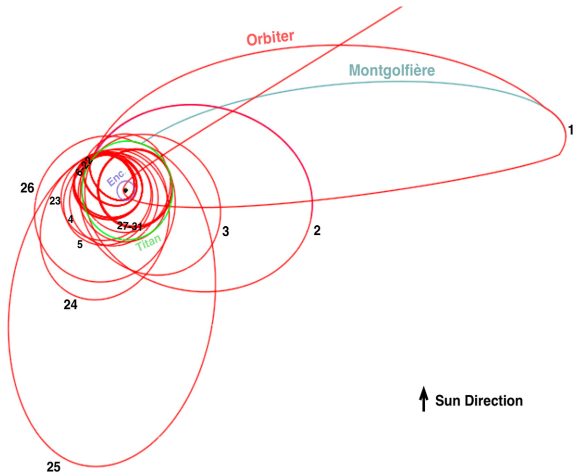


Figure 4.3-2. Planned Saturn Tour Phase showing orbits numbered from SOI to TOI.

ties for science. In addition to the close Rhea flyby shown in **Table 4.3-7**, there are several other distant flybys of the icy moons shown in **Table 4.3-8** These flybys provide many targets of opportunity that add to the TSSM tour science beyond the focus on Titan and Enceladus used for the tour design.

In Phase A, the probability of impacting Enceladus after a total spacecraft failure will be examined to ensure compliance with planetary protection requirements. Analysis similar to that done for the Juno trajectory will ensure that the final tour design provides a probability of contamination of the sub-surface water reservoir on Enceladus less than 10^{-4}. Planetary protection for Titan in the event of spacecraft failure both during the tour and the later Titan Orbit Phase will also be examined. However, as explained in §4.7, it is currently thought that the probability of any randomly selected spot on Titan would have liquid water near enough to the surface to be concern is less than 10^{-5}. If this value holds upon further study, special trajectory design for planetary protection of Titan would only be required for the disposal stage.

4.3.5 Delivery of *In Situ* Elements

Two *in situ* elements provided by ESA are carried on the orbiter and released at the beginning of the tour. After SOI, a Balloon Targeting Maneuver (BTM) targets the montgolfière to 20°N, where winds are thought to be strong enough at the montgolfière's 10 km altitude to maximize the likelihood of at least one circumnavigation of Titan. After BTM, there is a three-week period from January 16, 2030 to February 6 during which the montgolfière can be released. Following release, on February 7, the orbiter performs a Periapsis Raise Maneuver (PRM) to lower its Titan V-infinity to 2.8 km/s for the upcoming Enceladus flybys. On the next orbit, the lander is released (also with a 21-day window) prior to the second Titan flyby and targeted to Kraken Mare, a hydrocarbon sea in Titan's arctic region. **FO-1** details the timeline for release and arrival of the *in situ* elements.

Table 4.3-8. Distant flybys <100,000 km.

Date	Moon	Altitude [km]	Vinf [km/s]
28-Oct-29	Enceladus	23,000	17.5
31-Oct-30	Tethys	46,000	6.6
14-Nov-30	Mimas	86,000	11.3
14-Nov-30	Tethys	87,000	6.1
4-Dec-30	Tethys	73,000	5.7
26-Dec-30	Enceladus	32,000	2.8
4-Jan-31	Rhea	55,000	5.2

The montgolfière arrives in daylight in the morning, so that it has ~6 Earth days until Titan nightfall. For the lander, its landing site in Kraken Mare is above Titan's arctic circle and does not get sunlight at the time of the mission due to northern winter. Therefore, the lander is designed with a lamp for illumination of its immediate vicinity and does not require daylight. (Kraken Mare would be a vast featureless expanse of open Sea at the landing site and little information would be gained from imaging beyond the immediate vicinity.) When the lander arrives, the Sun is ~22° below the horizon, but a gibbous Saturn is visible and provides 2.5 times the light of a full moon at Earth. An alternate delivery of the Lander is also possible which would arrive in twilight when the Sun is only ~8° below the horizon and Saturn is in a crescent phase providing roughly the illumination of one full moon. The trade between these two delivery options will be examined in further detail in Phase A.

The delivery of both elements is operationally robust in offering three-week windows for the releases. Should this robustness not be sufficient, contingency tours could be developed (as were developed for Cassini-Huygens) that would enable either element to be delivered on a subsequent Titan flyby. Such contingencies would insert an additional orbit in the

***Table 4.3-9.** In situ element entry parameters.*

Parameter	Value
Montgolfière Destination	20° N at steady state
Montgolfière Interface Altitude	2000 km
Montgolfière Entry Speed	6.3 km/s
Montgolfière Entry Ang. Corridor	65° +/- 3° (3-sigma)
Mont. Release Vel. Uncertainty	35 mm/s (1-sigma)
Lander Landing Site	72°N 310°W, Kraken Mare
Lander 3-σ Landing Footprint	600 km E-W X 160 km N-S
Lander Interface Altitude	2000 km
Lander Entry Speed	3 km/s
Lander Entry Angle Corridor	65° +/- 1.5° (3-sigma)
Lander Release Vel. Uncertainty	35 mm/s 1-sigma

tour and shift TOI 6–8 months later for the montgolfière and 2–4 months later for the lander. Such contingencies could be developed during Phase E when the tour design is finalized if the project determines that the three-week windows in the current design are not sufficiently robust.

Table 4.3-9 details the delivery targets for the *in situ* elements along with the delivery dispersions. This table also gives the landing ellipse. **Figure 4.3-3** shows the landing ellipse for the lander on a polar plot of Kraken Mare.

A covariance study was done for another case with release of the montgolfière and lander several months prior to SOI. This study found that the principal sources of error at the 2000 km interface were: 1) time from release to entry, 2) errors introduced by the separation mechanism, and 3) radiation pressure from any RPS on the *in situ* element. Moreover, it was found that this error at the interface altitude was a small factor in determining the size of the landing ellipse compared to errors introduced by winds during descent. A good approximation of the relative effects of these two error sources is that the delivery errors at the interface lead to the smaller North-South axis of the landing ellipse, and that wind induced errors lead to the larger East-West axis. To decrease the North-South axis would require reducing delivery errors (e.g., by reducing the time from release to entry) and to decrease the East-West axis would require reducing the effect of the winds (e.g., by reducing the descent time with a smaller parachute).

The constraints in **Table 4.3-9** arose from this study, which showed that velocity uncertainties on the order of 20–25 mm/s on the *in situ* elements after release were achievable with a Cassini-Huygens like delivery scheme. The entry angle constraints and delivery dispersions at the interface reflected in **Table 4.3-9** are possible with velocity uncertainties of ~35 mm/s. This analysis will be re-visited in Phase A.

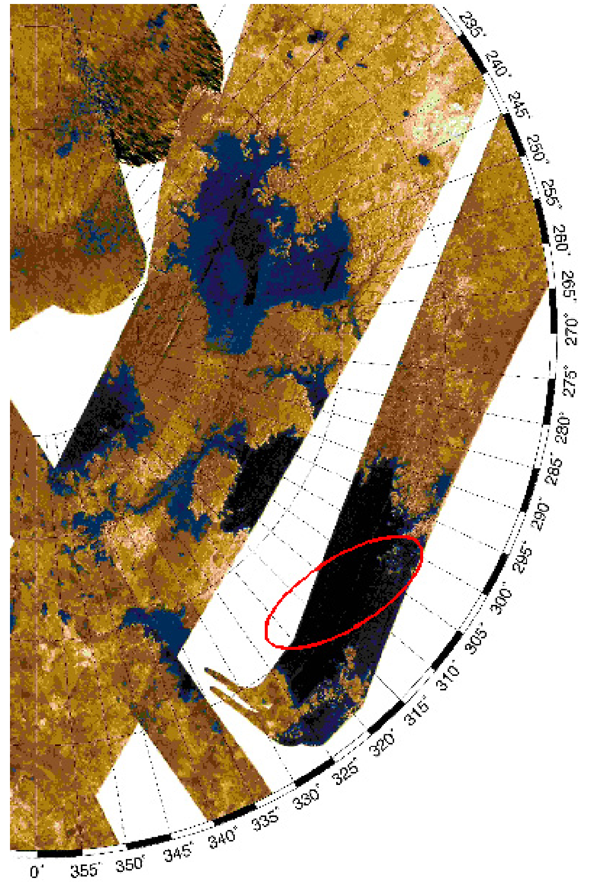


***Figure 4.3-3.** Kraken Mare landing site.*

4.3.6 *In Situ* Element Relay

The montgolfière is a long-lived vehicle with an MMRTG power source. During its nominal six month mission the primary relay for the montgolfière is through the TSSM orbiter, although limited direct to Earth (DTE) communication is also possible. The relay will occur during some Titan flybys and while the orbiter is in Saturn orbit. This will allow a total data transfer of >1.3 Tb.

The lander is a short-lived battery powered probe with a nominal three-hour surface mission and a six-hour descent. Its only relay will be to the TSSM orbiter, which will provide a dedicated nine-hour relay period during the second Titan flyby with a capability of 3.4 Gb of data.

The critical events of entry, descent, and landing (EDL) for the lander and the entry, descent, and inflation (EDI) for the montgolfière are visible for radio monitoring via relay with the orbiter. The montgolfière's EDI could also be monitored from Earth, but that is not required. **FO-1** details the relay geometry for both elements during these periods. This critical event coverage is described in more detail in §4.4.3.4.

The relay from the orbiter to both elements is X-band through the High Gain Antenna (HGA). When the orbiter is > ~500,000 km in range the HGA beam width is sufficient to cover the entire visible hemisphere of Titan. However, when the range is sufficiently close, the footprint from the HGA is smaller than the *a priori* knowledge of either *in situ* element's location. For the lander, this occurs when the range is < ~30,000 km. The montgolfière is a mobile platform that must be located at every flyby.

To maintain the link in these situations, the orbiter will maintain and update an on-board estimate of the location of each *in situ* element during the relay. This is done by periodically performing a two-axis peak scan with the HGA to locate each *in situ* element within the HGA footprint. For the lander, this will enable the link to be maintained to the minimum range of ~3,000 km at the end of the 9 hr relay period. For the montgolfière, this will enable the link to be maintained through close Titan flybys.

The montgolfière will have the ability to detect the orbiter's transmitted signal and turn its own 0.5 m HGA in the direction of the orbiter to maximize communication rates without complex (given the lack of guide-stars) on-board attitude determination.

Finally, there will be periods of ~8 days in duration when the montgolfière is not in communication with the orbiter due to occultation by Titan. The winds at the 10 km altitude at which the montgolfière is designed to float, will move the montgolfière along lines of relatively constant latitude. This allows for coarse interpolation of its position through these periods to predict windows when the montgolfière will reemerge, into the orbiter's view. In general, the orbiter will be far enough away that the HGA will cover all of Titan when the montgolfière reemerges. (Special cases that are an exception to this, if they occur, will be identified during Phase A.) Once the link is established, a peak scan can then be used to get a fix on the montgolfière's location.

An additional requirement on the montgolfière is to reconstruct its location to 1 km knowledge accuracy in latitude and longitude for the interpretation of measurements taken by the montgolfière. Angular data from the orbiter's peak scan and the pointing of the montgolfière's HGA will help in this determination, but it will primarily be done via radiometric tracking employing range data and two-way Doppler from the orbiter. Post-processing correlation of the time-stamped images from the montgolfière to global Titan maps, created by TSSM in the Circular Orbit Phase, will provide even more precise knowledge of the montgolfière's position for science data analysis. This terrain-based optical navigation will also provide a way to estimate the montgolfière's position during periods when it is not in view.

The location determination of the *in situ* elements both for link pointing and *in situ* element trajectory reconstruction will be studied in more detail during Phase A.

Appendix J, §4.4.3.4, and **Foldout 5** provide more details regarding the orbiter to *in situ* element communication relays and associated data rates.

4.3.7 Titan Aerobraking

Titan Orbit Insertion (TOI) places the orbiter into a 15,000 km by 720 km 85° inclinstion elliptical orbit around Titan. Over several orbits, Saturn's gravitational perturbations then raise periapsis of this orbit before pushing it lower into the atmosphere. During these atmospheric passes, drag lowers the orbit apoapsis (see **Figure 4.3-4**). As the periapsis altitude nears 600 km, the heating on the spacecraft reaches a peak heating of 0.23 W/cm^2, which is below the aerobraking trajectory design limit of 0.25 W/cm^2 (a value well below typical heating loads for other aerobraking missions) and a maneuver is performed to raise periapsis. This maneuver is sized such that Saturn's gravity will subsequently lower the periapsis back into Titan's atmosphere. Each of these periapsis raise maneuver would have to be performed no more often than every three days to avoid the heating limits (see

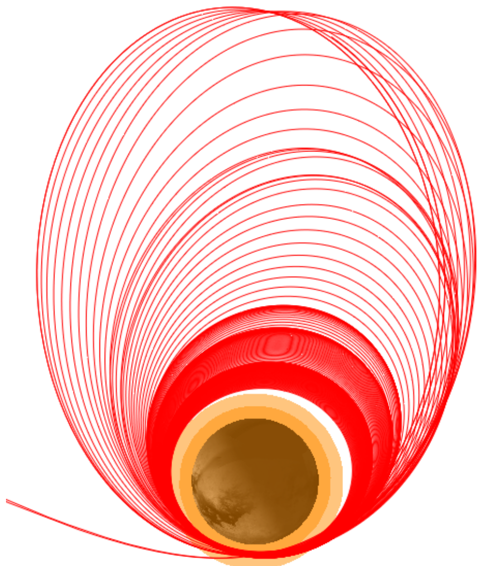


Figure 4.3-4. Aerobraking phase orbits.

Figure 4.3-5 through **Figure 4.3-10**). This 3-day minimum spacing gives multiple backup opportunities to make up for missed maneuvers.

This phase enables many low altitude passes for *in situ* sampling of Titan's atmosphere as well as *in situ* measurement of Titan's intrinsic magnetic field below the ionosphere. **Figure 4.3-10** details the altitude versus latitude coverage during this phase showing complete coverage of the southern hemisphere below 1000 km altitude. Additionally, the high apoapses at the beginning of this phase enable global monitoring of Titan for clouds and other features of the troposphere and excellent geometry for Titan limb sounding.

The aerobraking sequence is designed using an atmospheric model developed for the study by experts on Titan's atmosphere using Cassini and Huygens data. The density provided by this model was then scaled up for aerobraking by a factor of 2.2 to conservatively bound the modeling uncertainty in comparison to observations. This model will be updated based on Cassini extended and extended-extended mission data prior to Saturn arrival. In addition, several low-altitude flybys shown in **Table 4.3-7** provide an opportunity to directly measure the atmosphere prior to the start of aerobraking so as to confirm the Titan atmospheric models early enough to allow for adjustments to the aerobraking trajectory.

Titan's atmosphere is more stable than Mars' with a predicted 1-sigma density variation of 15% pass-to-pass compared to 30% 1-sigma for Mars. In addition, a hazard to Mars aerobraking is planet-wide dust storms that can pop up over a span of a few days and increase density by a factor of 10. Titan does not experience anything similar to these planet-wide storms, and the aerobraking operations are much more benign as a result.

In fact, atmospheric variability is a small effect in comparison to perturbations from Saturn's gravity that will raise and lower periapsis of the elliptical aerobraking orbit. Most of the 79 m/s of maintenance ΔV shown in **Figure 4.3-5** is required to counteract Saturnian perturbations. If the Aerobraking Phase were shortened to 30 days, Saturn's effect is reduced and the maintenance ΔV is reduced to only 63 m/s. The optimal balance of aerobraking duration and science return will be further studied in Phase A.

After two months of aerobraking, the apoapsis is lowered to the 1500 km altitude of the circular orbit and an 85 m/s circularization maneuver is performed to raise periapsis and establish the circular mapping orbit. Over the course of the Aerobraking Phase the orbiter achieves ~400 m/s of ΔV from atmospheric drag (see **Figure 4.3-6**) for a net savings of ~240 m/s.

Attitude stability during aerobraking is maintained by placing the spacecraft in a passively stable attitude shown in **Figure 4.3-11** which has the large drag area of the HGA behind the center of mass of the spacecraft like a shuttlecock. Prior to the start of aerobraking, the HGA will be placed using the current estimate of the center of mass location so as to minimize attitude transients about the stable attitude (see also §4.4.3.6 and §4.6.3.2).

Figure 4.3-12 shows the portions of the spacecraft that are exposed to the ram direction of the flow during aerobraking. The majority of this area is the HGA and the engine cover. (which gives a drag area of 12.5 m^2 for the spacecraft from the 4 m HGA). The PMS instrument has a sampling port that is aligned with the flow. As discussed in §4.2.1.2, HiRIS is the only instrument to need a cover during aerobraking.

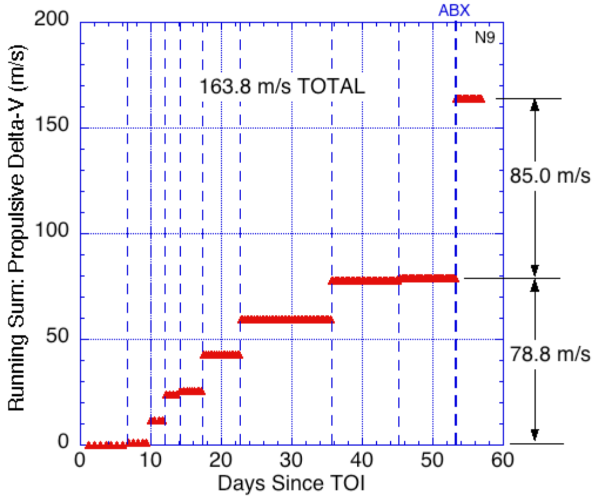


Figure 4.3-5. Aerobraking maneuvers.

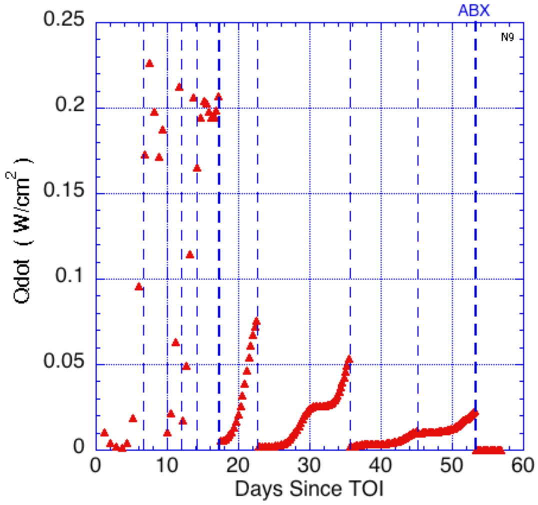


Figure 4.3-8. Aerobraking heat loads.

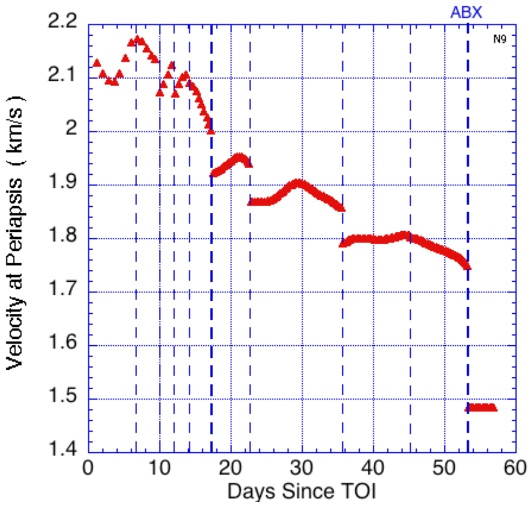


Figure 4.3-6. Aerobraking ΔV savings.

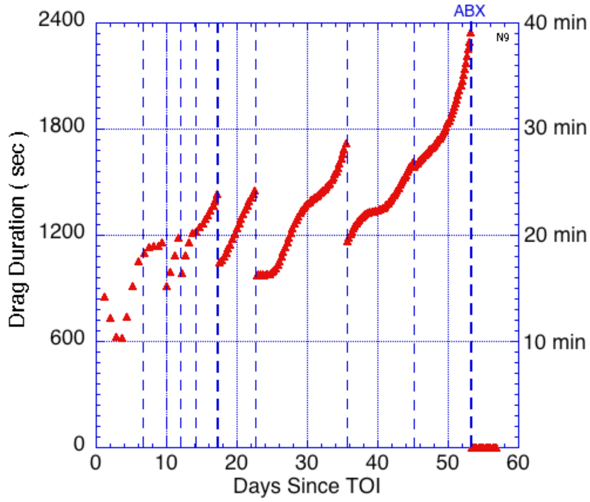


Figure 4.3-9. Aerobraking pass duration.

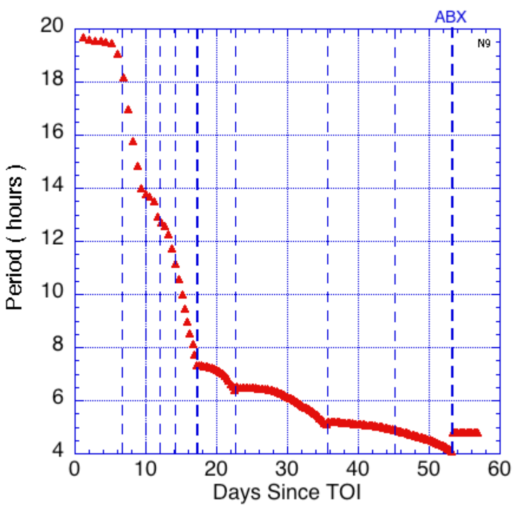


Figure 4.3-7. Aerobraking orbit periods.

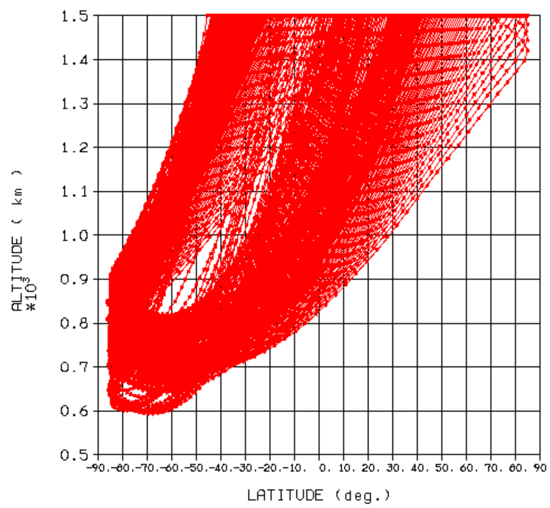


Figure 4.3-10. Aerobraking latitude coverage.

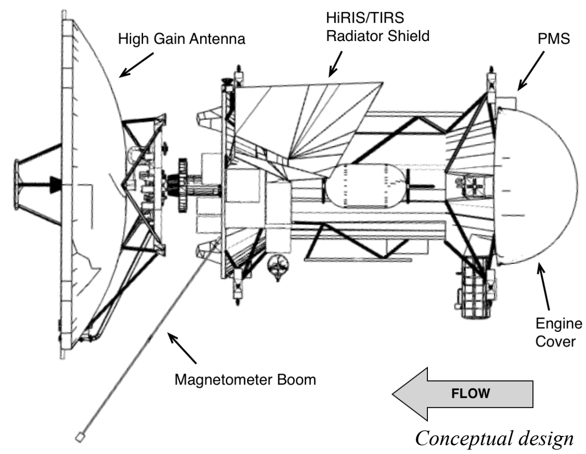


Figure 4.3-11. Attitude during aerobraking.

All portions of the spacecraft will be designed to be tolerant to greater than 0.25 W/cm^2. The heat loading for each part of the spacecraft will be examined in more detail in Phase A.

4.3.8 Titan Circular Orbit

After aerobraking, the orbiter enters a 1500 km circular orbit at an inclination of 85°. The 1500 km altitude was chosen because of the negligible drag at this altitude allows for long spacecraft life, while still being at a reasonable distance from the surface. However, lower altitudes are possible for reasonable amounts of orbit maintenance (see **Figure 4.3-13**). This altitude will be re-examined and fine-tuned as the mission progresses.

The 85° inclination was chosen because it is near-polar and allows coverage of almost all of Titan's surface. By being slightly off-polar, Saturn's gravity will rotate the orbit plane. Saturn's orbit results in an apparent motion of the Sun in Titan's sky of ~9°/year. By choosing 85° as opposed to 95° inclination the orbit plane rotation will add to the Sun's apparent motion leading to a ~20°/yr motion of the Sun with respect to the orbit plane. This is a ~2.5 hr change in Local Solar Time (LST) of the orbit's descending and ascending nodes over the 20-month Titan Circular Orbit Phase.

The orbit plane starts with a descending node at a 11:30 am LST which rotates to 9:00 am by end of mission (see **FO-1**). This allows a range of Solar phase angles from low phase angles that provide high signal to noise

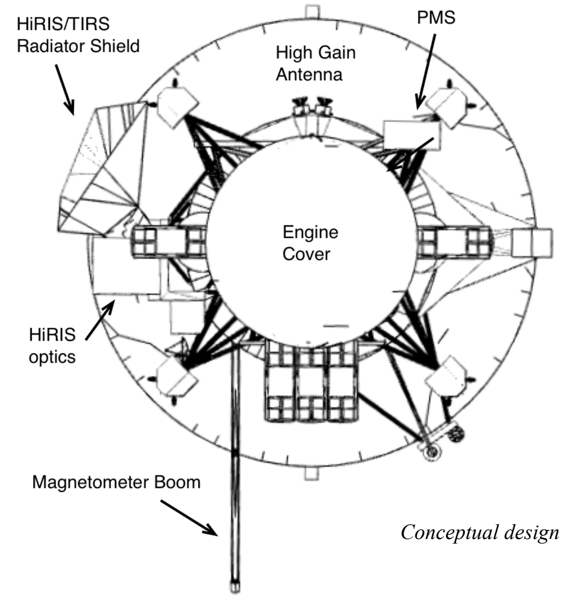


Figure 4.3-12. Spacecraft exposure to flow.

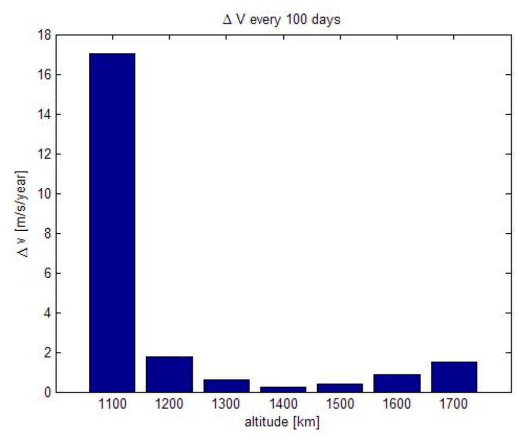


Figure 4.3-13. Circular orbit maintenance ΔV.

for optical remote sensing to higher phase observations that provide greater shadowing to highlight relief. In addition, as shown on **FO-1**, this plane rotation allows Titan atmospheric radio occultations at a wide variety of latitudes.

4.3.9 Decommissioning and Disposal

After the end of the prime mission there is a six-month Decommissioning and Disposal Phase during which the spacecraft will impact Titan. At the end of the mission, a 15 m/s maneuver lowers periapsis to ~1340 km altitude. Perturbations from Saturn's gravity will

increase the eccentricity of this orbit over a period of 4–5 months until the periapsis decreases to ~1000 km and atmospheric drag accelerates the decay. From this point, the orbit will decay and impact in about a week. Small maneuvers made before and during this final descent can move the final impact point several hundred km on Titan's surface. This enables the final impact to be targeted away from any places on Titan's surface where liquid water may be near the surface and that would be of planetary protection concern.

4.3.10 Mission ΔV

Table 4.3-10 shows the mission chemical ΔV budget for both bi-prop and mono-prop

Table 4.3-10. *Mission ΔV budget.*

	Bi-Prop ΔV [m/s]	Mono-Prop ΔV [m/s]	Description
Interplanetary TCMs	4	1	Several small maneuvers needed after SEP stage release for final Saturn targeting. *SEP stage is released prior to these maneuvers.*
SOI	746	0	**Saturn Orbit Insertion** modeled as Finite Burn with gravity losses. Three trades could reduce the size of SOI: 1. Longer flight time to Saturn, 2. Longer flight time from SOI to first Titan flyby, 3. Moving ring plane crossing to gap below D-ring.
SOI-CU (3%)	22	0	**SOI Clean-Up** estimated as 3% of SOI to represent a 3-sigma case. By estimating the largest maneuver's cleanup as 3-sigma, TSSM is robust to at least one 3-sigma cleanup.
BTM	261	0	**Balloon Targeting Maneuver** modeled to deliver montgolfière to Titan entry target. Increasing the period of the initial Saturn orbit may reduce this ΔV. This could be possible without increasing the total tour duration.
BTM-CU (2%)	5	1	**BTM Clean-Up** ΔV in one or two maneuvers estimated as 2% of BTM to represent a 2-sigma case. Additional 1 m/s of mono-prop ΔV added for precision targeting. *The montgolfière is released after these maneuvers.*
PRM	309	0	**Periapsis Raise Maneuver** to set-up first Titan flyby. Increasing the period of the initial Saturn orbit may reduce this ΔV. This could be possible without increasing the total tour duration.
PRM-CU (2%)	6	0	**PRM Clean-Up** estimated as 2% of PRM to represent a 2-sigma case.
LTM	7	0	**Lander Targeting Maneuver** modeled to deliver lander to Kraken Mare.
LTM-CU	0	1	**LTM Clean-Up** estimated as 1 or 2 maneuvers totaling 1 m/s of mono-prop ΔV. *Lander is released following these maneuvers.*
ODM	110	0	**Orbiter Delay Maneuver** provides 9 hour delay from lander entry at Titan and orbiter closest approach at the end of the lander relay.
ODM-CU (2%)	2	0	**ODM Clean-Up** estimated as 2% of ODM to represent a 2-sigma case.
Tour Deterministic	40	0	Deterministic ΔV found from integrated tour trajectory. This ΔV is required primarily for targeting of Enceladus flybys. Otherwise, the tour would be nearly ballistic.
Tour Margin (50%)	20	0	This margin leaves rooms for future refinement of the tour design.
Leveraging Pump-Down	197	0	ΔV to decrease Titan V-infinity prior to TOI. This ΔV may be reduced by adding 1–2 months to the tour duration.
Beta Adjustment	25	0	ΔV needed (in two maneuvers) to achieve the proper orientation of the Titan orbit with respect to the Sun (i.e., a descending node crossing at 11:30 am LST). This ΔV could be reduced with refinements to the tour design.
Tour Phase Statistical	12	12	Estimate of the statistical ΔV needed for the entire tour phase extrapolated from the Cassini Extended Mission tour design experience. This estimate is 0.5 m/s of bi-prop and 0.5 m/s of mono-prop per targeted flyby (24).
TOI	388	0	**Titan Orbit Insertion** modeled as Finite Burn with gravity losses. This ΔV could be reduced with further refinement of the leveraging pump-down and of the aerobraking phase.
TOI-CU (2%)	8	0	**TOI Clean-Up** estimated as 2% of TOI to represent a 2-sigma case.
Aerobraking Maintenance	79	0	ΔV from simulated 2 month aerobraking design with drag and Saturn gravity. This ΔV can be reduced with a shorter Aerobraking Phase (e.g., 63 m/s for a 30 day aerobraking).
Aerobraking Margin (15%)	12	0	This margin is to maintain flexibility in the future design of the aerobraking maneuver strategy. However, aerobraking maintenance ΔV may also decrease with this refinement.
Circularization	85	0	ΔV required to raise periapsis and to circularize the orbit at the end of aerobraking. This ΔV would be reduced for a lower circular orbit. (to ~65 m/s for 1400 km or ~45 m/s for 1300 km)
Circular Orbit Maintenance	0	4	ΔV needed to maintain circular orbit from simulation with drag and Saturn gravity + 100% margin. This large margin is to maintain operational flexibility.
De-Orbit and Disposal	18	2	15 m/s for de-orbit plus additional ΔV margin to control the 6-month orbit decay.
Total	**2356**	**21**	

along with the associated rationale for each line item. The deterministic mission ΔV has been verified by high fidelity modeling of the trajectory (see §4.3.12). The statistical ΔV is estimated, with rationales given in the table, based on Cassini and Galileo historical experience.

The ΔV in this table is that needed to implement the Baseline mission design along with margin to cover values that were either estimated (e.g., statistical and mono-prop ΔV) or likely to grow as the trajectory is better optimized for science. Maneuvers that will change little as the mission design evolves need little margin (e.g., SOI, TOI, PRM). The tour ΔV, however, benefits from the margins shown to enable flexibility in the upcoming refinement of the tour design. Similarly, the aerobraking maintenance ΔV margin is to allow for flexibility in new maneuver strategies to allow better optimization for spacecraft operations. Should changes to the mission design as the project progresses require more ΔV than shown, §5.0 describes how the interplanetary SEP trajectory can be modified to provide significantly more margin.

The propellant masses in the MEL in Appendix E are calculated with the ΔV in **Table 4.3-10** assuming an I_{sp} of 323 s for the bi-prop system and 217 s for mono-prop. This is done using the full launch vehicle capability and assuming the release of the SEP stage and *in situ* elements at the times described in the table. Additional propellant mass is added for attitude control thrusting (50 kg), pressurant (12 kg) and tank residuals (65 kg).

4.3.11 Backup Launch Opportunities

The Baseline mission launches in 2020 on a SEP EVEE trajectory, which is detailed in §4.3.3. The primary backup launch opportunity is a 2022 EVEE gravity assist trajectory detailed in **Table 4.3-11** and **Table 4.3-12**. The 2022 backup gives the maxium xenon load (550 kg after 10% margin is added) used for sizing the SEP stage tanks.

The 2022 trajectory has a very similar chemical ΔV budget to the 2020 trajectory (see **Table 4.3-10**). The difference being in that SOI decreases to 689 m/s from 746 m/s. Another backup option exists six months earlier in 2021, but it arrives at Saturn the same time as the 2022 trajectory. **Table 4.3-13** describes the features of these trajectories such as flight time and size of SOI in other years. All of these trajectories are assumed to use the same orbiter and *in situ* element designs, and the table shows they achieve similar mass capability for the orbiter as the Baseline trajectory with lower chemical propellant loads than the Baseline.

Table 4.3-11. *21-day launch period (2022).*

	Beginning of Launch Period	Middle of Launch Period	End of Launch Period
Date	Mar 28, 2022	Apr 6	Apr 16
C_3 [km²/s²]	1.44	1.40	1.44
DLA [deg]	18.8°	20.4°	20.9°
Launch Mass [kg]	6175	6175	6175
SEP ΔV (km/s)	3.33	3.33	3.33
Xenon Fuel (kg)	500	500	500

Table 4.3-12. *Interplanetary events (2022).*

Event	Date / Altitude
Launch	Mar 27–Apr 16
Begin SEP Thrusting	May 26, 2022
Earth-1	May 25, 2023 / 15770 km
Venus	Sep 19, 2023 / 5550 km
Earth-2	Jun 4, 2024 / 1550 km
Earth-3	May 9, 2026 / 600 km
End SEP Thrusting	Aug 7, 2027
SOI (689 m/s)	Sep 30, 2031

Table 4.3-13. *SEP trajectories in alternate launch years.*

Path	Launch Date	Arrival Date	FT to Saturn [y]	Launch C3 [km²/s²]	Launch Mass [kg] (A551)	Xenon Fuel [kg]	Saturn V_∞ [km/s]	SOI ΔV [m/s]	Chem. Fuel [kg]	Orbiter Mass [kg]
EEVEE	Jul 2018	Jan 2028	9.5	1.2	6200	500	6.20	680	2432	1705
EVEE	Jan 2019	Feb 2028	9.0	1.2	6200	500	6.20	680	2432	1705
EVEE	Sep 2020	Oct 2029	9.0	0.8	6240	445	6.66	745	2533	1703
EEVEE	Oct 2021	Mar 2031	9.4	1.4	6175	500	6.10	670	2414	1704
EVEE	Apr 2022	Feb 2031	8.8	1.4	6175	500	6.10	670	2414	1704

4.3.12 Trajectory Modeling Assumptions

Prior to this study, it was widely assumed that a Titan mission with an orbiter and *in situ* elements would require Titan aerocapture for the orbiter, especially with an Atlas V launch. This study developed several new and innovative approaches to accomplish TSSM without aerocapture. In order to verify the correctness of these new approaches and the associated ΔV budget, the trajectory was integrated from launch to end of mission in a high fidelity force model including n-body perturbations and Titan atmospheric drag when appropriate (see §4.3.7). Forces dependant on the spacecraft design and attitude were neglected (e.g., solar radiation pressure, RPS radiation pressure, etc), but these forces are not expected to change the ΔV budget or the correctness of the trajectory.

Another benefit of this high fidelity end-to-end integration beyond higher confidence in the ΔV values is confidence in the interconnections between the different mission phases. Particularly, the connection between the end of the Saturn Tour Phase and the start of the Titan Orbit Phase is especially complex to model, requiring n-body gravity models to correctly determine the initial orbit orientation and the stability of the initial aerobraking orbit.

4.4 Flight System Design and Development

4.4.1 Flight System Overview

The Flight System design for TSSM was derived from a number of sources. The elimination of aerocapture from the mission architecture rendered the 2007 Titan Explorer study Flight System concept of limited applicability to the present propulsive capture design. The 2007 Europa Explorer and Jupiter System Observer concepts, which also made use of propulsive capture, actually provided a better stepping off point for the present study. These earlier designs, combined with lessons learned from Cassini and input in a number of areas from the New Horizons and MESSENGER spacecraft, led to a Flight System that minimizes mass and power, while maximizing science return for the TSSM.

The TSSM orbiter Flight System (**Figure 4.4-1**) consists of a three-axis stabilized spacecraft powered by RPSs. The Flight System includes an articulated 4 m high gain antenna (HGA) using Ka-band for high rate science data downlink. A planning payload of six instruments plus radio science is accommodated with instruments located on a payload deck, as well as other locations on the spacecraft dictated by their observational requirements. Accommodation for two *in situ* elements is provided at attach points along the body of the spacecraft. Five Advanced Stirling Radioisotope Generators (ASRGs) would power the spacecraft, with four providing about 540 W of electrical power at end of mission (EOM, about 13 years after launch) and the fifth unit carried as a spare. Redundant 25 A-hr Lithium-ion (Li-ion) batteries provide for power demands that exceed the ASRG capability during the science mapping orbit and other times during the mission. The fully margined Flight System mass at launch, is 6203 kg with respect to the currently quoted Atlas V 551 capability of 6265 kg to the required launch C_3.

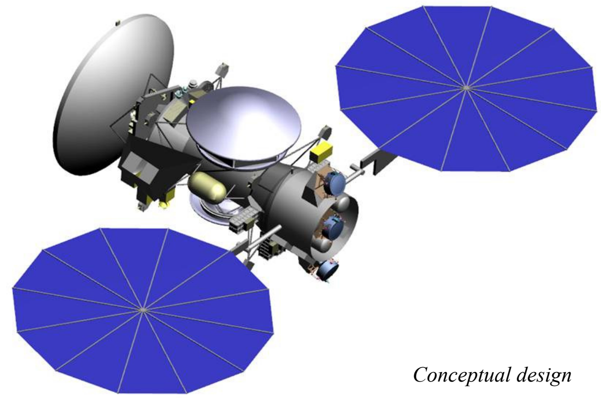


Figure 4.4-1. *TSSM Flight System.*

The Command and Data Handling subsystem is built on JPL's Multi-mission System Architecture Platform (MSAP) for maximum commonality with other JPL designs. The data processing and handling architecture includes a dual-string RAD750 computer that is capable of performing all science and engineering functions. Data storage is implemented using 32 Gb of SDRAM dedicated for science and an additional 1.75 Gb of non-volatile flash memory allocated for engineering and science flight software, engineering telemetry, processing space, and margin.

Spacecraft attitude is controlled primarily with reaction wheels during science operations. Small 4.5 N thrusters located in coupled pairs are used to reduce post-launch separation rates, as well as to provide attitude control during cruise and aerobraking. These thrusters will also be used for desaturation of the reaction wheels.

The propulsion system has a dual-mode architecture, which includes a single gimbaled 890 N bipropellant main engine plus the 16, 4.5 N monopropellant thrusters used in the reaction control system (RCS). The total ΔV capability of the propulsion system with the full fuel load is 2377 m/s.

Waste heat from the ASRGs is exploited for thermal control to the maximum extent practical in order to reduce the use of electrical power for heaters. Radioisotope heater units (RHUs) and Variable RHUs are also employed to further reduce electrical requirements.

The TSSM Flight System incorporates a capable SEP stage for highly efficient ΔV augmentation during the first half of the cruise trajectory. The SEP stage for TSSM was developed as a simple, bolt-on augmentation built around and incorporating the function of a Launch Vehicle Adapter (LVA). The basic LVA structure is used to support two Orion-derived 7.5 kW Ultraflex solar array wings, as well as three NEXT ion thrusters, power processing units (PPUs), xenon tanks, and electronics necessary to the control and operation of this self-contained stage. Interfaces with the launch vehicle and orbiter have been kept as simple as possible to allow the flexibility to operate with or without the SEP stage without significant changes to orbiter configuration.

Configuration

The conceptual configuration of the Baseline Flight System is shown in **Figure 4.4-2** and **Figure 4.4-3**. The major configuration drivers were as follows:

- Nadir fields-of-view for the remote sensing instruments and clear fields-of-view for instrument radiators
- Propellant tanks optimized to minimize tank and structure mass
- Atlas V 551 fairing envelope and access door size and number (three doors, each at 1.22 m × 1.83 m)
- Accommodation of 5 ASRGs, a 4 m HGA, and two aeroshells within the fairing
- Achieving sufficient HGA mounting stiffness to achieve tight pointing accuracy requirements (0.7 mrad) of a 4 m dish operating in Ka-band
- ASRG accommodation for use of waste heat in thermal control
- RCS thrusters (16 thrusters, each 4.5 N) with placement driven by the coupling requirement and plume impingement consideration on instruments, *in situ* envelopes, and ASRGs

4.4.2 Systems Engineering

Most design concepts employed in this mission are flight proven and present few unique challenges. However, several areas that are important to any mission of this type will continue to be the focus of systems engineering evaluations as concept development continues. Some of these areas of particular interest in the engineering of the Flight System are discussed in the following sections.

4.4.2.1 Assumptions, Requirements, and Constraints

The list below summarizes key requirements and constraints that have driven the TSSM Flight System design.

- The Flight System design should minimize the use of new technologies to minimize cost and schedule risk.
- A total of seven MMRTGs worth of ^{238}Pu is available to the mission, including that provided to ESA for *in situ* elements.
- The mission radiation design dose is benign (<15 krad behind 100 mil aluminum) which must be tolerated with a radiation design factor (RDF) of at least 2.
- The required total SEP ΔV is 2750 m/s, chemical ΔV is ~2400 m/s.
- The Flight System shall support a launch date in the 2018–2020 timeframe.
- The Flight System design should be able to return all Level 1 science through DSN 34 m ground stations.
- The Flight System shall accommodate *in situ* elements to be provided by ESA.
- Saturn tour science, including Enceladus flybys shall be included in the mission design.
- Minimum heliocentric range is 0.7 AU.

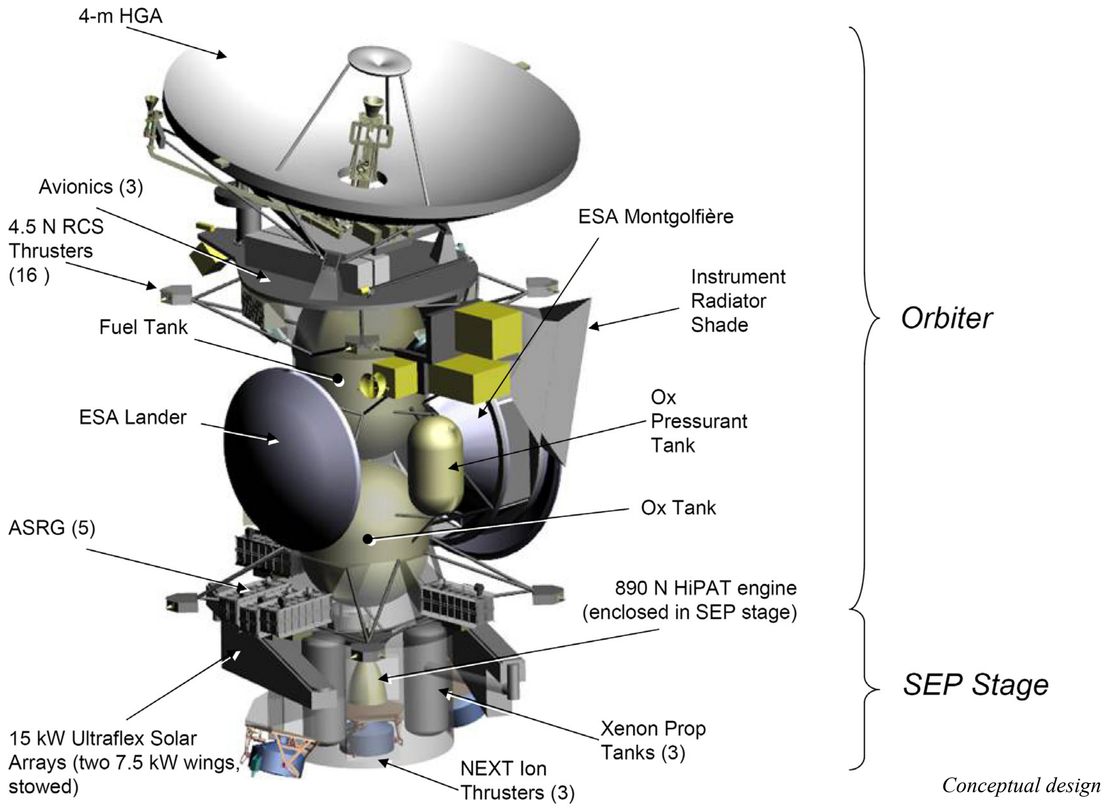


Figure 4.4-2. *Orbiter configuration.*

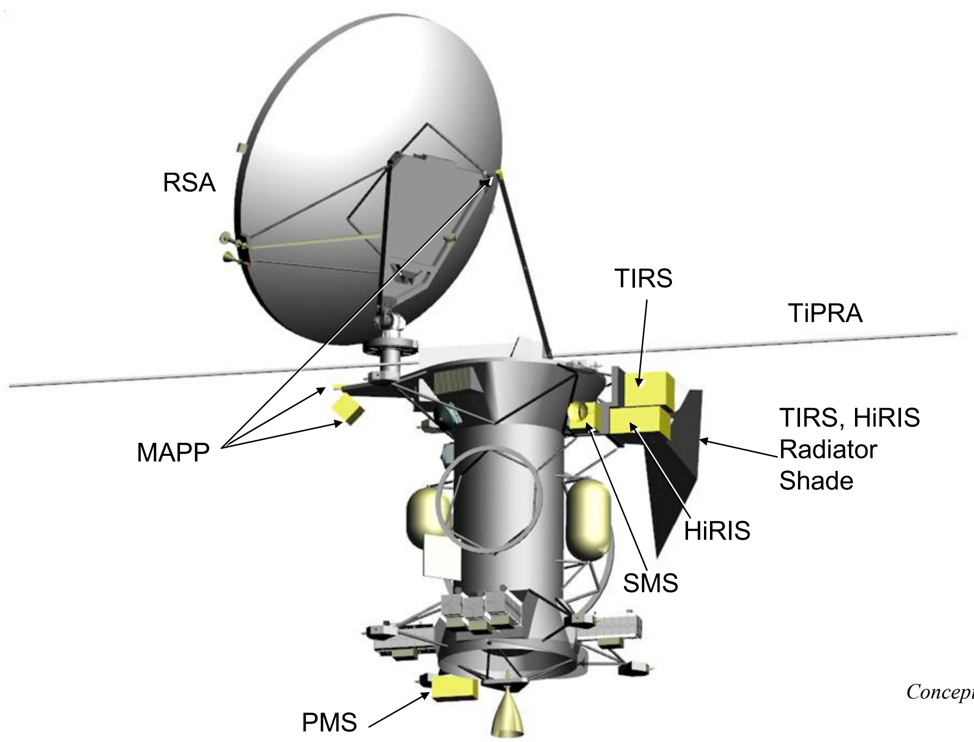


Figure 4.4-3. *Instrument layout.*

4.4.2.2 Orbiter Power Source

In the initial charter for the study, a programmatic constraint was imposed dictating that only solar arrays or MMRTGs should be used to power the Flight System. While the SEP stage is ideally suited to the use of solar power for its limited period of use early in the mission, it was recognized that radioisotope power would be required for the orbiter primary mission, given Saturn's extended solar range. The initial Flight System design incorporated five MMRTGs to provide power, which, when considering the likely requirement to provide one MMRTG to the montgolfière and a number of RHUs to the orbiter and *in situ* vehicles, kept the total mission inventory below the stated allocation of 7 MMRTGs worth of ^{238}Pu.

Midway through the study, the Ground Rules were changed to allow the use of Advanced Stirling Radioisotope Generators (ASRGs) in consideration of the limited inventory of ^{238}Pu and the continued progress of ASRG development. Furthermore, it was stated that the studies could assume that either ASRGs or MMRTGs could be adopted with an equivalent level of risk. Given the removal of risk as a discriminator between RPS types, and the benefit to NASA of investigating the integration issues for a Flagship mission, the team elected to adopt ASRGs for the Baseline design. Advantages over the MMRTG include lower mass, higher output power per unit, lower degradation rate with time, and lower unit cost. Additionally, the adoption of ASRGs would help to extend NASA's available ^{238}Pu inventory by using only a quarter of the amount needed by an equivalent number of MMRTGs.

The team recognizes that ASRG development is not yet complete, nor has a flight ASRG been assembled or flown. For this reason the orbiter design and operational scenarios have maintained a concept that is equally compatible with MMRTGs for the power subsystem. Reversion to the MMRTG design would result in a reduction of EOM power of about 35 W and an increase in mass of about 52 kg, both of which could be accommodated without impact to achieving science objectives of the mission.

4.4.2.2.1 Impacts of ASRG

The implementation of ASRGs in the TSSM design brings with it a number of differences from accommodation of MMRTGs. Among these, three stand out as having potentially significant impacts to the Flight System design. These include:

- Waste heat quantity and quality for use in thermal control
- Electromagnetic interference (EMI)
- Vibration imparted to the spacecraft

The first of these concerns is a result of the higher efficiency of the ASRG when compared with the MMRTG. The more than four-fold improvement in conversion efficiency results in less than a quarter of the waste heat that would be available from an MMRTG for use in thermal control of spacecraft elements (primarily fuel and oxidizer tanks). In addition, the waste heat that is available from the ASRGs is at a much lower temperature than that from the MMRTGs, causing additional difficulties in its utilization. An innovative capillary pumped loop heat pipe solution was developed to address this issue as described in §4.4.3.2.

The question of EMI from ASRGs is often raised and was investigated for this study. Specified values for AC and DC magnetic field emissions and E-field radiated emissions are given in the ASRG User Interface Control Document (ICD) that was provided to the study team. These values were used along with the ASRG mounting geometry to calculate combined field strengths at each instrument location. Results were assessed by the instrument engineers and showed the calculated levels to be below those that would cause concern for any instrument.

The ASRG, being based on a reciprocating piston engine will induce a certain amount of vibration, similarly to Stirling-based cryocoolers. The ASRG design attempts to mitigate this vibration by mounting two opposing Stirling engines in a single unit and coordinating their piston strokes to ensure cancellation of vibration to the maximum extent possible. The latest version of the ASRG ICD gives a value of 35 N for the maximum dynamic force transmitted to the host spacecraft. Very preliminary assessment of the ICD value would indicate that some measure of additional vibration

damping might be required to ensure that no significant impact is seen at the instruments. However, in the course of investigating the ASRG development program it became clear that the listed vibration specification was based on an earlier design for the ASRG. The unit currently under development for flight has been shown in testing to exhibit vibration levels of ~1.7 N, more than an order of magnitude lower than the spec value. At this level it is likely that no additional vibration mitigation would be needed.

At this point in the design of the TSSM Flight System and the development of the ASRG it is not possible to fully assess all of the impacts of the implementation of this emerging power system. ASRG accommodation in the overall Flight System will require ongoing systems engineering, analysis and coordination with ASRG development efforts, which will be a significant focus in Phase A.

4.4.2.3 Long-Life—High Reliability

JPL's Flight Project Practices and Design Principles were founded on experience from long life, highly reliable, deep space missions. These missions have successfully operated over long periods of time and over great distances with limited human interaction. Lessons learned from Pioneer, Voyager, Galileo, Cassini, and others, are incorporated into the TSSM design including extreme value worst case analysis, parts stress analysis, block redundancy, autonomous fault recovery, cross-strapping, internal redundancy and functional redundancy in appropriate combinations to eliminate all non-exempt single-point failures (SPFs).

In keeping with best system engineering practices full redundancy is incorporated in the TSSM design to the maximum extent, with the exception of typical areas of standard SPF exemptions (e.g., primary structure, propellant tanks, etc.). An additional exception is the use of a single main engine. The decision to baseline this single engine design was made as a result of a propulsion subsystem trade study and was vetted by experienced propulsion and systems engineers with experience from Voyager, Galileo, and Cassini at a propulsion subsystem review. This trade is planned to be further assessed in Phase A. The planning payload is also currently single string with minimal selected redundancy; further evaluation and recommendations for additional redundancy for instruments will be made during the AO and instrument selection process.

All redundancy, fault-protection logic and cross-strapping circuitry is validated in the system testbeds or in integration and test prior to launch. For any non-exempt SPFs, a risk evaluation will be performed. As a result, the SPF will be eliminated or a waiver to the Single Point Failure policy will be generated (requiring institutional approval).

In parts selection and qualification, the project is governed by the JPL Institutional Part Program Requirements as tailored for TSSM. In compliance with these requirements, all critical electronics are subjected to destructive physical analysis (DPA), residual gas analysis (RGA) and particle impact noise detection (PIND), as appropriate. An Approved Parts and Materials List (APML) for Outer Planet Flagship Mission (OPFM) Projects (IOM #5143-08-079, JPL 2008a) has been developed to be used as the selection source for electrical, electronic, and electromechanical (EEE) parts and materials.

4.4.2.4 Fault Protection and Operability

Given the duration of the mission and the one-way light time from the Saturn system, autonomy is needed to handle Flight System safety issues. A system of monitors and responses will mitigate, isolate, and recover from off-nominal behaviors if encountered during the mission. In keeping with proven design practice for missions of this type, onboard fault protection algorithms will halt normal operations and place the Flight System into a safe configuration, awaiting ground response when they detect a potentially unsafe condition. An exception to this would be when a Flight System is executing a time critical operation, such as an orbit insertion.

The TSSM fault protection design is based on an underlying architecture consisting of:

- Built-in hardware fault detection and recovery. For example, error detection and recovery within memory devices.
- Lower-level fault protection that is built into the hardware device drivers and managers. These modules detect and perform local recovery from faults when possible.

- Performance-level fault protection that consists of a series of performance monitors that examine and respond to specific subsystems for performance deviations or fault indications
- System-level fault protection that is made up of software fault monitors and responses to handle faults that are detected, but uncorrected by lower level fault protection because they require a system level coordinated response. For example, the shedding of loads because of a power failure.
- Flight software health monitors perform self-tests, and keep track of computer resets and health.
- Flight software watchdog timers monitor overall health of the onboard control system, and force configuration changes when the system stops operating properly.
- In addition, operations and built-in software and hardware behaviors will employ additional strategies that contribute to robust functionality by working in the presence of isolated faults that may occur. For example, a command will be sent twice in case the first command is lost or rejected because of errors.

All fault monitors and responses can be individually enabled or disabled by command or configuration file.

Operability has been a significant topic of focus for this study. TSSM has profited particularly in this area through the direct experience of a number of the operations and Flight System team members who are also currently members of Cassini's mission team. Beyond this, a task was undertaken to systematically extract lessons learned from operations on a number of relevant missions, including not only Cassini-Huygens, but also MRO, New Horizons, and MESSENGER (see Appendix K). This study resulted in a number of recommendations in areas including mission design, Flight System and ground system interfaces, science operations, testing, and management. These recommendations were then factored back into the study to take full advantage of the wealth of relevant experience provided by these ongoing missions.

4.4.2.5 Radiation

The TSSM Flight System would be subjected to three major radiation environment sources: 1) solar energetic particles during the interplanetary cruise, 2) trapped particles during the Saturn tour, and 3) particles from the onboard ASRGs.

The Interplanetary Cruise Phase is defined with a launch in September 2020 and Saturn arrival in October 2029. It uses an Earth-Venus-Earth-Earth gravity assist trajectory to reach Saturn. The JPL solar proton model (Divine et al. 1990) at 95% confidence level is used to estimate the solar proton environment during the cruise.

After SOI, the spacecraft spends 2 years in Saturn orbit, with multiple flybys of Enceladus and Titan, and then orbits Titan for another 2 years. The SATRAD model (Garrett et al. 2005) is used for the radiation environment estimate at Saturn. Titan is outside of the Saturn radiation belt, and thus the Titan Orbit Phase of the mission will not accumulate any additional radiation exposure.

The TSSM Flight System carries six radioisotope power systems (RPSs); five ASRGs on the spacecraft and one MMRTG on the montgolfière. The total dose from RPSs was conservatively estimated assuming all six RPSs were MMRTGs to ensure compatibility with the MMRTG-powered option. RPS dose was estimated using the dose versus distance contours that were generated for the MSL project. The nominal distance of electronics from RPSs was based on the spacecraft configuration drawings.

Figure 4.4-4 shows the total mission dose depth curve without the RPS contribution included. The dose is primarily solar with a 10% contribution from Saturn by the end of mission. It is assumed that RPSs contribute an additional 1776 rad(Si) regardless of shielding thickness. **Figure 4.4-5** shows the time history of the dose with a 100 mil aluminum spherical shell shielding, again without RPSs.

The TSSM mission elements will experience a benign radiation environment. Total mission dose from charged particles on electronics behind 100 mils aluminum spherical shielding would be 12.6 krad. With the addition of the dose from the MMRTG analysis, the new mission dose is 14.4 krads (RDF=1). Given this value, the radiation risk of the project is low and a standard radiation mitigation approach (e.g., the one for MSL) can be

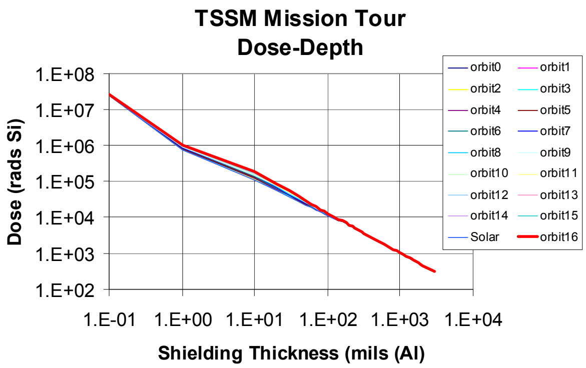


Figure 4.4-4. Aluminum spherical shell dose-depth curve for TSSM showing cruise and orbit contributions (excluding RPS contribution).

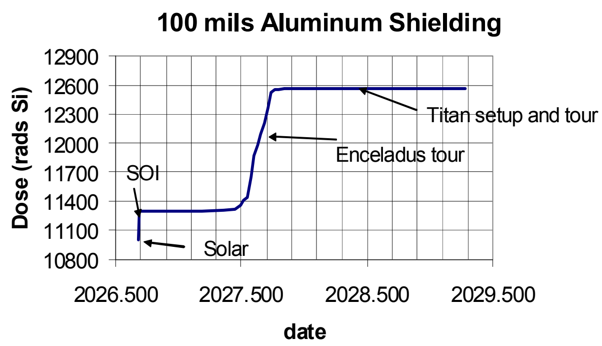


Figure 4.4-5. Time history of total ionizing dose (TID) excluding RPS contribution.

adopted for electronic parts, materials, and science detectors/sensors without the need for additional shielding or specialized parts.

4.4.2.6 Planetary Protection

As described in more detail in §4.7, the approach to planetary protection compliance for the TSSM Flight System will have limited impact on the Flight System design and processing. The planetary protection approach will involve ensuring that the risk of "inadvertent contamination of a liquid water body" is less than 10^{-4}. The primary means of meeting this requirement is through analysis to show 1) that unintentional impact with Enceladus and Titan during the Saturn system tour will be below $1x10^{-3}$ and 2) that end of mission deorbit scenarios will ensure that the Flight System avoids any geographic or thermal anomalies that could harbor a local environment conducive to the existence of liquid water. Further analysis will be performed to confirm that local heating by ASRGs or their general purpose heat source (GPHS) modules will not transgress "limits of life" and/or will not impact on the surface at the end of the mission co-located with contaminated hardware. Planetary protection implementation for ESA-provided *in situ* elements will be addressed separately by ESA, although budgetary accommodation is made for interface management.

4.4.2.7 Payload Interfaces

As described in §4.2, the spacecraft will accommodate the payload by providing for a view in the nadir direction for the remote sensing instruments when in orbit around Titan, as well as providing for observations during the Saturn Tour Phase and Enceladus flybys. The spacecraft body must maintain pointing control to 0.3 mrad and stability to 2.4 μrad over 5 s. Payload accommodation for all electrical, thermal and mechanical interfaces will be developed between the spacecraft development team and the payload teams. The system functional block diagram in **Foldout 2 (FO-2)** shows the data interfaces for the instruments. Instrument fields of view and volumes are shown in **Figure 4.2-1**. Instrument data rates are noted in **Table 4.2-2**.

4.4.2.8 Launch Vehicle Interface

In the launch configuration, the TSSM Flight System is mounted to the Atlas V 551 launch vehicle (LV) as shown in **Figure 4.4-6**. The SEP stage structure acts as a Launch Vehicle Adapter and is mounted to the LV via a separation interface. The separation of the Flight System from the launch vehicle and the orbiter from the SEP stage is assumed to be via a linear separation device (Superzip).

In order to fit within the Atlas V fairing envelope, three assemblies on the orbiter are launched in a folded/stowed configuration. The HGA, TiPRA antenna, and magnetometer boom are launched stowed and deployed during the mission. In addition to these, the SEP stage contains two Ultraflex solar arrays, which are stowed during launch and deployed prior to SEP thrusting.

4.4.2.9 Resource Margin Summary

The TSSM design includes robust margins in all critical areas. A conservative margin approach has been taken which provides significant room for mission concept modifications without large impacts on the primary

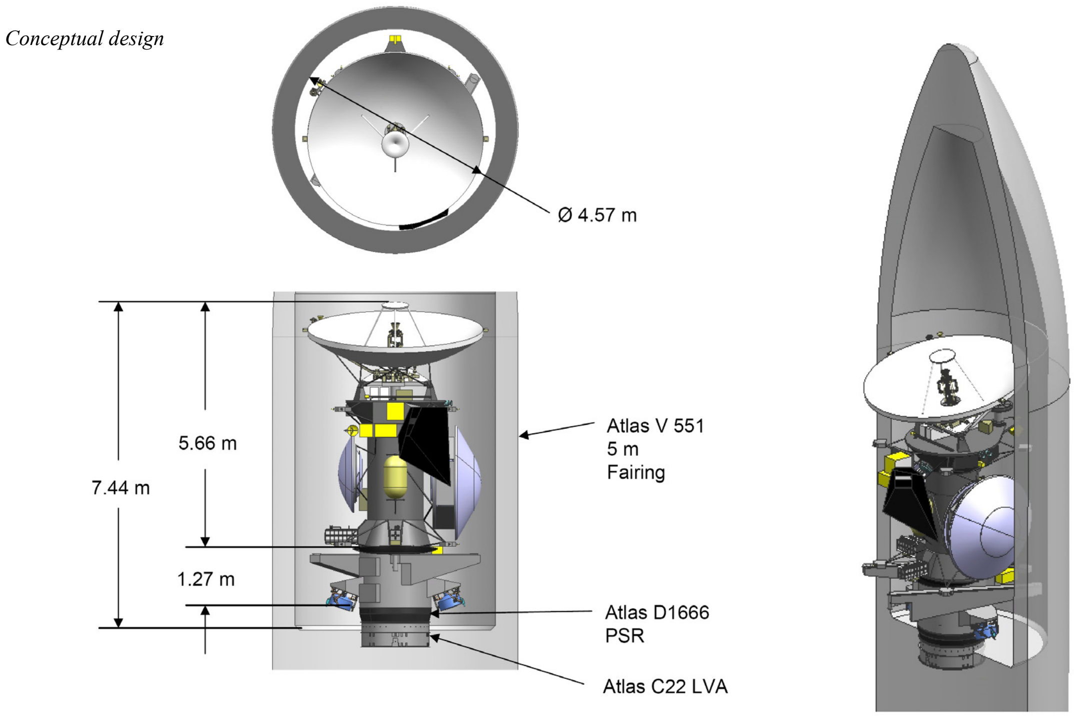


Figure 4.4-6. *Flight System launch configuration in Atlas V 551 fairing.*

Table 4.4-1. *Example of calculating required margin and corresponding contingency.*

	Value	
Max Possible Resource Value (MPRV)	100 kg	Example Value
Required Margin per Study Guidelines	33 kg	= 33% * MPRV
Maximum Allowable CBE (Max CBE)	67 kg	= MPRV – Req'd Mrgn
Contingency Percentage to apply to CBE to achieve MPRV	49.3%	= (MPRV) – 1 (Max CBE)
Check Calculation	100 kg	= Max CBE * (100% + 49.3%)

Table 4.4-2. *Example of calculating additional and system margins.*

	Value	
Current Best Estimate (CBE)	200 kg	Example value
CBE + Contingency to achieve required margin	299 kg	= CBE * 1.493
Max Possible Resource Value (MPRV)	325 kg	Example Value (e.g. Launch Vehicle Capability)
Additional Margin (above required 33%)	26 kg	= MPRV – (CBE*1.493)
System Margin	38%	=(MPRV – CBE) x 100 MPRV

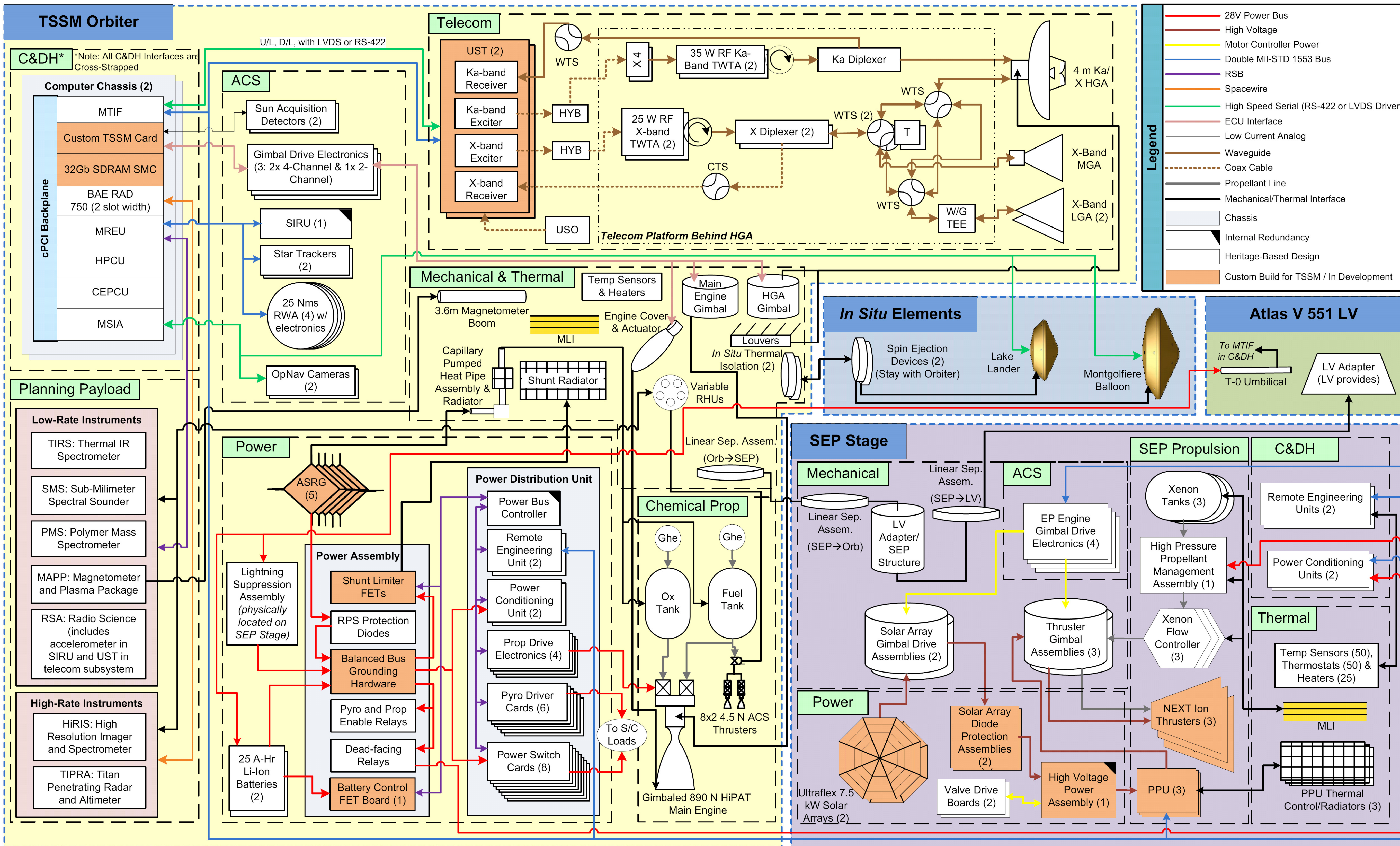
resource constraints (number of RPS units and launch vehicle injected mass capability).

The Ground Rules state that, in general, a 33% margin should be held in all areas, calculated per the method described in the JPL Design Principles and Practices (DPP), where the margin is calculated as the Maximum Possible Resource Value (MPRV) minus the Proposed Resource Value (aka Current Best Estimate, CBE). For TSSM, the MPRV correlates to the Atlas V 551 launch vehicle capability for calculating mass margin and to the EOM power output of four ASRGs for the power margin calculation. The margin percentage is then calculated as:

$$Mrgn\ (\%) = \frac{MPRV - CBE}{MPRV} \times 100$$

Holding 33% margin against the MPRV, per this method, translates into adding 49% contingency onto the Current Best Estimate (CBE) values, as shown in **Table 4.4-1**.

Table 4.4-2 shows an example of calculating additional margin and system margin. Additional margin is defined as any margin beyond the required 33% mandated in the study guidelines. System margin is then the


TSSM Orbiter
C&DH*
*Note: All C&DH Interfaces are Cross-Strapped
Computer Chassis (2)
cPCI Backplane
MTIF
Custom TSSM Card
32Gb SDRAM SMC
BAE RAD 750 (2 slot width)
MREU
HPCU
CEPCU
MSIA
U/L, D/L, with LVDS or RS-422
ACS
Sun Acquisition Detectors (2)
Gimbal Drive Electronics (3: 2x 4-Channel & 1x 2-Channel)
SIRU (1)
Star Trackers (2)
25 Nms RWA (4) w/ electronics
OpNav Cameras (2)
Telecom
UST (2)
Ka-band Receiver
Ka-band Exciter
X-band Exciter
X-band Receiver
WTS
HYB
HYB
USO
X4
35 W RF Ka-Band TWTA (2)
Ka Diplexer
25 W RF X-band TWTA (2)
X Diplexer (2)
CTS
WTS
WTS (2)
T
WTS
W/G TEE
4 m Ka/ X HGA
X-Band MGA
X-Band LGA (2)
Telecom Platform Behind HGA
Mechanical & Thermal
Temp Sensors & Heaters
Main Engine Gimbal
HGA Gimbal
3.6m Magnetometer Boom
MLI
Engine Cover & Actuator
Louvers
In Situ Thermal Isolation (2)
Capillary Pumped Heat Pipe Assembly & Radiator
Shunt Radiator
Variable RHUs
Linear Sep. Assem. (Orb→SEP)
Planning Payload
Low-Rate Instruments
TIRS: Thermal IR Spectrometer
SMS: Sub-Milimeter Spectral Sounder
PMS: Polymer Mass Spectrometer
MAPP: Magnetometer and Plasma Package
RSA: Radio Science (includes accelerometer in SIRU and UST in telecom subsystem
High-Rate Instruments
HiRIS: High Resolution Imager and Spectrometer
TIPRA: Titan Penetrating Radar and Altimeter
Power
ASRG (5)
Lightning Suppression Assembly (physically located on SEP Stage)
Power Assembly
Shunt Limiter FETs
RPS Protection Diodes
Balanced Bus Grounding Hardware
Pyro and Prop Enable Relays
Dead-facing Relays
Battery Control FET Board (1)
25 A-Hr Li-Ion Batteries (2)
Power Distribution Unit
Power Bus Controller
Remote Engineering Unit (2)
Power Conditioning Unit (2)
Prop Drive Electronics (4)
Pyro Driver Cards (6)
Power Switch Cards (8)
To S/C Loads
Chemical Prop
Ghe
Ghe
Ox Tank
Fuel Tank
8x2 4.5 N ACS Thrusters
Gimbaled 890 N HiPAT Main Engine
In Situ Elements
Spin Ejection Devices (2) (Stay with Orbiter)
Lake Lander
Montgolfiere Balloon
Atlas V 551 LV
To MTIF in C&DH
T-0 Umbilical
LV Adapter (LV provides)
SEP Stage
Mechanical
Linear Sep. Assem. (SEP→Orb)
LV Adapter/ SEP Structure
Linear Sep. Assem. (SEP→LV)
ACS
EP Engine Gimbal Drive Electronics (4)
Solar Array Gimbal Drive Assemblies (2)
Thruster Gimbal Assemblies (3)
SEP Propulsion
Xenon Tanks (3)
High Pressure Propellant Management Assembly (1)
Xenon Flow Controller (3)
NEXT Ion Thrusters (3)
C&DH
Remote Engineering Units (2)
Power Conditioning Units (2)
Thermal
Temp Sensors (50), Thermostats (50) & Heaters (25)
MLI
PPU Thermal Control/Radiators (3)
Power
Ultraflex 7.5 kW Solar Arrays (2)
Solar Array Diode Protection Assemblies (2)
Valve Drive Boards (2)
High Voltage Power Assembly (1)
PPU (3)
Legend
28V Power Bus
High Voltage
Motor Controller Power
Double Mil-STD 1553 Bus
RSB
Spacewire
High Speed Serial (RS-422 or LVDS Drivers)
ECU Interface
Low Current Analog
Waveguide
Coax Cable
Propellant Line
Mechanical/Thermal Interface
Chassis
Internal Redundancy
Heritage-Based Design
Custom Build for TSSM / In Development

total margin measured against the Maximum Possible Resource Value (MPRV) and can be thought of as the required margin plus the additional margin. To be compliant with the study guidelines, the system margin has to be greater than or equal to 33%.

System-Level Mass Summary

The TSSM Flight System has a total launched wet mass of 6203 kg, and is comprised of a 1613 kg dry orbiter with 2528 kg of bi-propellants, a 778 kg dry SEP stage with 451 kg (includes 10% additional propellant for margin) of xenon propellant for its NEXT-based ion thrusters, two ESA-provided *in situ* vehicles: a 600 kg montgolfière and a 190 kg lander, as well as 43 kg of ESA-provided support equipment that stays with the orbiter after *in situ* vehicle deployment. The orbiter propellant mass is sized for the entire 6265 kg injected mass capability of the Atlas V 551 minus the SEP stage, per JPL Design Principles and Practices. See **Table 4.4-3** for the TSSM mass summary.

The *in situ* masses are treated as allocations (no additional mass margin kept by the NASA portion of the mission). The *in situ* elements are both slated to be released post-SOI, with the montgolfiére being released on the first

Table 4.4-3. *Mass summary for TSSM.*

TSSM Mass Equipment List	Flight System Mass, kg			Comments
	CBE	Cont.	CBE + Cont.	
Orbiter Payload	108	33%	143	
Instrument Planning Payload	108	33%	143	HiRIS, TIPRA, PMS, SMS, TIRS, MAPP, RSA
Orbiter Flight System	973	31%	1272	
Power (w/o RPS)	64	30%	83	Power distribution, converters, & switches, and 25 Ahr battery
C&DH	32	17%	37	Redundant Rad750 SFC and 32Gb SDRAM for science
Telecom	64	27%	82	X/Ka 4m HGA, X MGA & LGAs, 35W Ka and 25W X TWTAs
Structures & Mechanisms	350	30%	456	S/C structure, In-situ support, HGA gimbal, & mag boom
Thermal	82	30%	106	Capillary loop heat pipes, Venus shield, shunt radiator, and (V)RHUs
Propulsion	154	27%	196	890N main engine, RCS thrusters, and COPV tanks
ACS	53	21%	64	Reaction wheels, SIRU, star trackers, sun sensors, and OpNav
Cabling	68	30%	89	7% of CBE S/C bus dry mass
RPS System	107	49%	160	Five ASRGs
Orbiter Total Dry	1081	31%	1414	Includes P/L, bus, and subsystem contingency
Additional System Margin			198	Additional cont. on S/C bus and P/L to obtain 33% margin
Orbiter Total Dry with req'd margin			1613	Includes P/L, bus, and system contingency
Orbiter Propellant			2528	Fuel, oxidizer, pressurant, residuals/holdup, and RCS prop
Orbiter Total Wet			4141	
ESA-Provided In-Situ Packages	833	0%	833	Includes ESA-provided spin ejection devices for each in-situ vehicle
Montgolfiere Balloon (plus spin eject device)	633	0%	633	Released at beginning of tour (post-SOI)
Lander (plus spin eject device)	200	0%	200	Released mid-tour (post SOI)
Orbiter + In-Situ Total (Wet)			4975	Orbiter & in-situ P/L, flight system, prop, and all contingency
SEP System	502	31%	655	
Power	96	30%	124	Two 7.5 kW solar array wings
C&DH	8	18%	10	REUs and PCUs
Structures & Mechanisms	154	29%	199	SEP structure doubles as LV adapter, Thruster & solar array gimbals
Thermal	38	47%	56	Tank and structure MLI, temp sensors, heaters, and PPU radiator
Propulsion	168	30%	218	Three NEXT-based ion thrusters with PPU and Xenon tankage
ACS	3	10%	3	Gimbal drive electronics
Cabling	34	30%	44	Includes SEP to orbiter cabling and harnesses to HVPA, PPU, etc.
LV Adapter (on SEP Stage)	20	30%	26	Non-structural elements of the LV adapter (fasteners, blankets, etc.)
SEP Stage Total Dry			681	Includes SEP system, LV adapter, and subsystem contingency
Additional System Margin			97	Additional cont. on SEP system & LV adapter to obtain 33% margin
SEP Stage Total Dry with req'd margin			778	Includes P/L, bus, and system contingency
SEP Propellant			451	Includes 10% additional propellant for margin
SEP Stage Total Wet			1229	Wet SEP stage with contingency to achieve 33% study margin
Total Launch Mass			6203	Entire wet spacecraft including In-situ, SEP stage, adapters, and contingencies
Atlas V 551 Capability			6265	EVEES SEP trajectory launched in 2020 on Atlas V 551
Additional Mass Margin			62	Mass margin beyond the required 33% margin
System Margin (33% required per study guidelines)			35%	TSSM accomodates a SEP stage, an ample orbiter P/L & *In-Situ* Elements with sufficient margin

Titan flyby after SOI and the lander being released at the second flyby. The orbiter propellant mass is sized to accommodate this release scenario.

With the exception of orbiter cabling, all mass estimates were provided by the engineers for their respective subsystem. The cabling mass estimate was computed as a percentage (7%) of the CBE Flight System dry mass. This approach is based on the cabling mass of several historical space missions and provides a reasonable estimate for designs at this phase.

Subsystem engineers evaluated the maturity of their designs and applied appropriate contingency at the component level. Then, system level mass (198 kg on the orbiter and 97 kg on the SEP stage) was added in order to achieve the 33% margin required by the study guidelines. The design currently has 62 kg of additional mass margin above this 33% mandate, which translates to a total system mass margin of 35%.

TSSM is baselining ASRGs as the RPS system used to power the mission. ASRG information was provided in the ASRG User ICD (912IC001299 rev4) and RPS Spec Sheets (2008 rev1). The ASRG mass consists of the 20.2 kg ASRG unit plus a spacecraft isolator of 1.23 kg. As the ASRG has not previously been flown, the full 49% contingency required to reach a 33% system mass margin was carried on the ASRG mass.

If TSSM were directed to use MMRTGs instead of ASRGs, there is sufficient mass margin to accommodate the design change without affecting the 33% overall margin, as shown in **Table 4.4-4**.

Table 4.4-4. *RPS mass accommodation.*

	5 ASRG	5 MMRTG	Comments
RPS Mass	107.2 kg	226 kg	MMRTG mass is NTE
Required Mass Margin	52.7 kg	0 kg	
Structural Support (includes 49% cont)	3.7 kg	6.7 kg	MMRTGs have additional structure for stacking.
Thermal Control (includes 49% cont)	33.6 kg	16 kg	ASRGs require capillary loop heat pipes. MMRTGs require shades to protect s/c from heat loads.
Total RPS System Impact on Mass	197.2 kg	248.7 kg	
Additional Mass Required to Implement MMRTG	**--**	**51.5 kg**	**TSSM has sufficient margin to accommodate MMRTGs**

System-Level Power Summary

The power estimates for each subsystem are identified in **Table 4.4-5**. In the table, the worst-case average payload power is shown in each of the orbital modes. The flyby mode instrument power reflects the full payload power on for the time around closest approach with the telecom system in standby. Negative values at the bottom of the table indicates periods where battery usage and/or telecom and payload duty cycling is implemented, as reflected in the scenario modeling tool. In all cases, a positive energy balance with 33% margin is maintained.

All power levels were provided by the subsystem engineers as Current Best Estimate (CBE) values. A system-level contingency of 49% was applied to the CBE (including losses) power to achieve the required 33% margin.

Power losses were calculated as 7% for wire, power switching, and power conversion losses, plus 20 W for power electronics assembly standby power, per the power subsystem engineer. Power losses from battery discharging and charging are taken into account by a scenario modeling tool used for scenario analysis.

The *in situ* elements are provided a power interface with the orbiter. The montgolfière is not expected to need additional orbiter power, as it has its own RPS. Although no specific requirements have been stated as yet for orbiter-provided lander power during cruise, ample power would be available to support the lander as requirements evolve.

In Titan orbit, there are three different science campaigns planned (see §4.6.3.2). All three campaigns are similar in their power consumption, as the campaigns were designed to optimize power usage across the scenarios. The worst case orbital power scenario of the three campaigns occurs during the Atmospheric Dynamics and Composition Campaign (Campaign 3). This average power comes from the scenario model and reflects an accurate depiction of the telecom and science instrument duty cycles discussed in §4.6, and it

Table 4.4-5. Power estimates for TSSM Flight System.

TSSM Power Modes (W)	Launch	SEP Cruise	Ballistic Cruise	Manuever (TCM)	SOI & TOI	*In situ* Relay	Tour Flyby	Aerobraking	Safe	Reaction Wheel Desat	On-Orbit with Telecom	On-Orbit no Telecom
*PLEASE NOTE: Orbital payload power is the average power experience during Campaign 3, the worst case orbital power scenario. This reflects a duty cycle on each of the instruments. Flyby payload power is the full instrument complement powered during the two hours around closest approach. Both the orbital scenarios and the flyby scenarios implement battery usage, as seen by the negative values at the bottom of the table.	3 hr	24 hr	24 hr	15 min	1 hr	25 min	120 min	24 hr	24 hr	1 hr	172.2 min	114.8 min
Orbiter Payload	0	0	0	0	0	0	182	0	0	0	55	55
Instrument Planning Payload	0	0	0	0	0	0	182*	0	0	0	55*	55*
Orbiter Flight System	159	339	243	316	316	295	245	248	241	258	315	227
Power Electronics Stand-by (losses tracked below)	20	20	20	20	20	20	20	20	20	20	20	20
C&DH	58	58	58	58	58	58	58	58	58	58	58	58
Telecom	0	69	69	69	69	79	29	69	69	29	99	29
Structures & Mechanisms	13	0	0	13	13	15	15	7	0	0	15	0
Thermal	22	33	33	33	33	33	33	33	33	33	33	33
Propulsion	3	19	19	76	76	1	1	17	17	32	1	1
ACS	44	86	44	48	48	90	90	44	44	86	90	86
Cabling	0	0	0	0	0	0	0	0	0	0	0	0
RPS System	0	0	0	0	0	0	0	0	0	0	0	0
SEP Power Accomodation (to be powered by Orbiter)	0	54	0	0	0	0	0	0	0	0	0	0
In Situ Power Accomodation (to be powered by Orbiter)	0	0	0	0	0	0	0	0	0	0	0	0
Flight System Total Without Losses (CBE)	159	339	243	316	316	295	426	248	241	258	370	282
Power Losses (7% for wire, switching, & conversion losses. Does not include battery recharge losses tracked in scenario tool)	10	22	16	21	21	19	28	16	15	17	24	18
Flight System Total With Losses (CBE)	169	361	258	337	337	314	455	264	256	274	394	300
Additional System Margin to achieve study req.	83	178	127	166	166	155	224	130	126	135	194	148
Flight System Total Power Demand with Req'd Margin	252	539	386	503	503	469	679	394	382	410	589	448
Four ASRG Capability	600	576	548	548	548	558	549	548	541	541	541	541
Additional Power Available	348	37	163	46	46	89	-130	154	159	132	-48	93

Negative value indicates battery usage implemented in this mode. In all cases a positive energy balance is maintained.

includes 49% contingency on the CBE plus power losses. The average orbital power load represents the RPS sizing case for the TSSM mission and results in the need for four ASRGs and a modest battery to cover the periods during each orbit when instantaneous power demands exceed available RPS power. Power requirements in the other phases of the mission, such as launch and safe mode, are then easily met as shown in **Table 4.4-5**.

To accommodate the potential failure of an ASRG, one additional unit is carried as a spare, for a total of five, but only four are used in power sizing. The four ASRGs produce 541 W total power at the end of the 13 year mission. All orbit mode calculations were done off this worst-case EOM degradation scenario to be conservative, the power available would actually be slightly better at the beginning of the Titan Orbit Phase.

Table 4.4-6. RPS power accommodation.

	4 ASRG	5 MMRTG
RPS Power BOM (per RPS)	150 W	125 W
Degradation Rate (per year)	0.8%	1.6%
RPS Power EOM (per RPS)	135 W	101 W
Total RPS Power Available at 13 year EOM	**540 W**	**505 W**
EOM Power Capability Difference	**--**	**35 W**

If TSSM were directed to use MMRTGs instead of ASRGs, there would be 35 W less power available at EOM, as shown in **Table 4.4-6**. TSSM had a converged scenario for the 5 MMRTG case prior to switching to ASRGs,

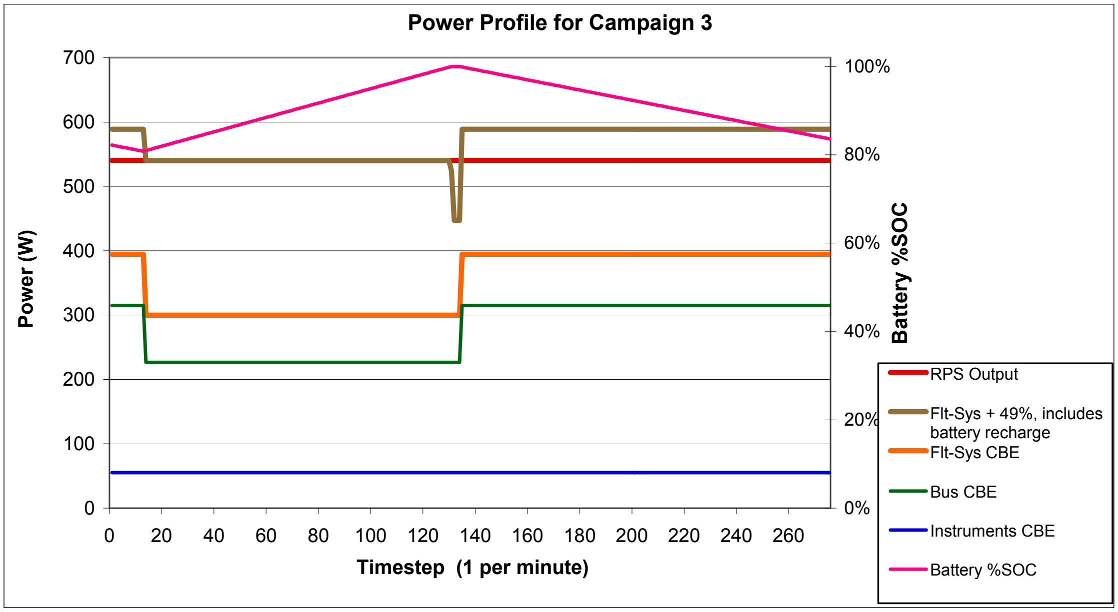


Figure 4.4-7. *Power profile for TSSM orbital atmospheric dynamics and composition observing scenario demonstrates worst case campaign performance while maintaining the required energy margins.*

and would therefore be able to revert back to this design without significant impact to science return or operational scenarios.

The power profile over one orbit in Campaign 3 is shown in **Figure 4.4-7**. The profile assumes an 8% recharge loss due to internal resistance and 80% charge efficiency, typical of Li-ion batteries. As this is a battery dominated, direct energy transfer power system, the ASRGs will operate at off-peak power voltages during battery charge and discharge.The battery depth of discharge (DOD) is limited to no more than 40%, though in this worst case orbital scenario it does not dip below 20% DOD. Assuming a 28 V bus, the energy demands are met with readily available 25 A-hr Li-ion batteries. The battery is charged each orbit when excess RPS power is available (generally during the times when not communicating to Earth).

4.4.3 Subsystem Descriptions

4.4.3.1 Structures and Mechanisms

The TSSM Structures and Mechanisms approach was based on analogy to prior concepts and missions, specifically Europa Orbiter concepts and Cassini. As with these earlier spacecraft, the major driver on the structures design is the propulsion tanks and the large amount of propellant necessary to accomplish the mission. For cost reasons, existing propellant tank sizes that have been flight qualified were originally baselined. Although the propulsion system design has evolved and adopted current industry standard composite overwrapped tanks, the Cassini heritage tank diameter of 1.24 m has been retained, resulting in tank heights for the TSSM Baseline mission of 1.4 m (oxidizer) and 1.8 m (fuel), which drove the orbiter stack height of 5.7 m. The SEP stage adds a further 1.3 m to the Flight System stack height in the launch configuration for an overall height of 7 m as seen in **Figure 4.4-8**.

The TSSM Structure subsystem consists of the SEP stage, the propulsion module structure, the electronics bus and a lower equipment module (**Figure 4.4-9**). The SEP stage structure is a machined Al structure that doubles as the spacecraft launch vehicle adapter, LVA. It interfaces directly with the Atlas V launch vehicle C-22 adapter. The SEP stage is released from the orbiter by a linear separation device similar to that used for the release of the SEP stage/orbiter stack from the Atlas launch vehicle. A system of guide rails is included on the SEP stage to prevent contact with the orbiter main engine during separation.

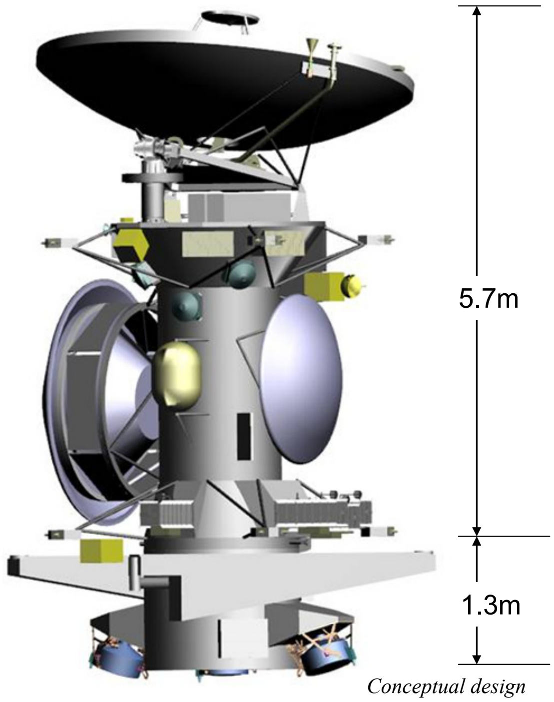


Figure 4.4-8. *TSSM launch configuration.*

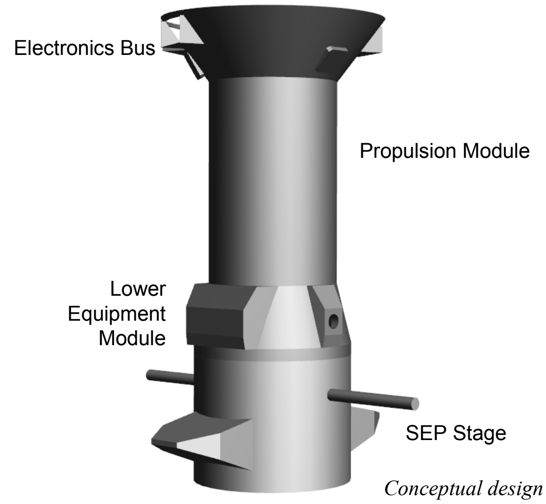


Figure 4.4-9. *Primary structural elements.*

Above the SEP stage is the lower equipment module which supports the ASRGs, the lower RCS thruster assemblies and the main engine. The ASRGs (five total) are mounted in three locations spaced 90 degrees apart. This configuration was chosen to limit the number of doors required in the launch vehicle fairing to three, which eases integration issues and has been vetted by the Launch Planning Office at KSC. Each ASRG mounts directly to the lower equipment module. The four lower RCS thruster assemblies are spaced 90 degrees apart and are supported onto the lower equipment module by a tripod support structure. The main engine is articulated using a 2-axis gimbal based on the Cassini main engine gimbal design and is mounted to the lower equipment module with three bi-pods. A deployable main engine cover is deployed during times the main engine is not in use. The deployable cover is based upon the Cassini main engine deployable cover. The lower equipment module is a machined Al structure.

The propulsion module structure is located above the lower equipment module. It is a large cylindrical structure made up of graphite composite face sheets and Al honeycomb core construction. The propulsion module structure supports the fuel, oxidizer and pressurant tanks. It also supports the two *in situ* elements. Each *in situ* element is attached to the propulsion module structure by three bi-pods and is released by an ESA-provided spin eject device.

Above the propulsion module structure is the electronics bus structure. The electronics bus structure is made up of machined Al. It houses the orbiter electronics and supports the Attitude Control Subsystem (ACS) reaction wheels, the upper thruster assemblies, science instruments and the 4 m HGA. The HGA is articulated using a 2-axis gimbal based on the MRO HGA design. During launch the HGA is restrained at three locations and released by firing three sep-nuts. The four upper RCS thruster assemblies are spaced 90 degrees apart and are supported onto the electronics bus structure by a tripod support structure.

The Flight System Structures and Mechanisms mass estimate was based upon finite element analysis and analogy to previous missions. A TSSM finite element model was developed to provide preliminary mass estimates for the TSSM SEP stage structure and the propulsion module structure.

The TSSM finite element model (FEM) is shown in **Figure 4.4-10**. Plate elements were used to represent the SEP stage structure, propulsion module structure, instrument deck and HGA assembly while lumped masses connected by rigid body elements were used to represent the propellant and propellant tank masses, thruster assemblies and the *in situ*

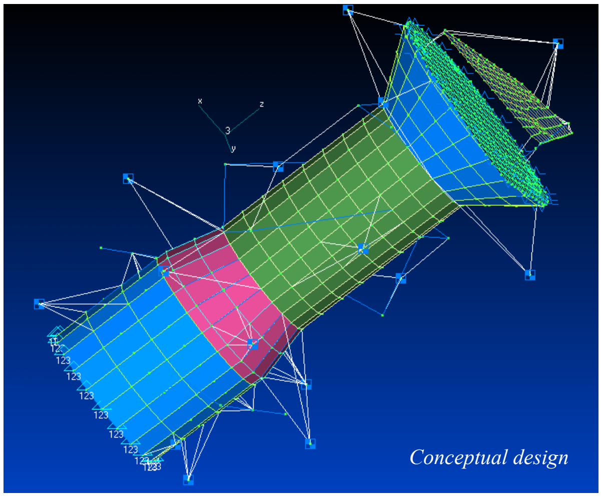


Figure 4.4-10. TSSM structural FEM.

elements and support structure. The remaining subsystem mass was smeared at appropriate locations on the structure of the FEM as non-structural mass. Two analysis cases were performed. The first case was a static launch load of 6.5 g applied in the axial direction. The second analysis case was a normal modes analysis. Positive margins were demonstrated from the static load case for the SEP stage structure and propulsion module structure. From the normal modes analysis, the first lateral and axial frequencies are 9.2 Hz and >40 Hz respectively. **Table 4.4-7** provides the normal modes analysis results.

Mass estimates for the remainder of the Structures and Mechanisms subsystem were based on analogy to previous missions' mass estimates for similar structures. The electronics bus mass was based upon the previous EO Study. The ASRG support structure mass estimate was based on Cassini and Mars Science Laboratory data. The two-axis gimbal estimate was based on the MRO telecom platform gimbal and the main engine gimbal and cover were based upon the Cassini engine gimbal mass and the Cassini deployable main engine cover, respectively. The magnetometer boom mass was taken from the MESSENGER as-built boom mass. Lastly, the linear separation devices (Superzip) were estimated using Cassini data scaled to the current TSSM LV interface diameter.

Note that all structure and mechanism CBE design mass estimates assume growth of other subsystems to their maximum allocations.

Table 4.4-7. TSSM normal modes summary.

Normal Modes		
Mode	**Freq (Hz)**	**Comment**
1	9.2	1st Lateral - X
2	9.7	1st Lateral - Y
3	20.2	Cylinder
4	22.7	Cylinder
5	24.6	Cylinder
6	25.9	Cylinder
7	29.0	Cylinder
8	30.1	Cylinder
9	32.0	Cylinder
10	33.1	Cylinder
11	33.6	Cylinder
12	36.4	Cylinder
13	40.4	Cylinder
14	41.6	Cylinder
15	44.4	Cylinder
16	45.4	1st Axial

4.4.3.2 Thermal Control Subsystem

The thermal control subsystem for the TSSM orbiter provides temperature control for the Flight System for all mission phases. The thermal control subsystem is designed to handle several environmental and spacecraft-related challenges:

- A large range of solar distances, ranging from 0.7 AU for the Venus gravity assist to 9.1 AU at Saturn.
- The Venus environment inputs resulting from the spacecraft-planet close approach.
- The requirement to minimize spacecraft electric power consumption
- Supporting instrument requirements to provide focal plane temperature levels as low as ~70 K
- Provision of *in situ* element thermal Interfaces
- Accommodation of the SEP stage

While the thermal design for this mission is unique due to the environmental and spacecraft characteristics, the thermal control subsystem utilizes flight proven thermal control elements, thus minimizing development risk. There are several engineering development requirements, but no new technology is required for this mission. The thermal control elements used in the design include multilayer insulation (MLI), thermal surfaces, thermal

conduction control, thermal louvers, electric heaters and thermostats, engineering sensors, radioisotope heater units (RHUs) both fixed and variable, shades (Sun/Venus, Instrument), and utilization of ASRG waste heat with capillary pumped thermal loops.

Effect of the Large Range of Solar Distances

The TSSM Flight System will experience a wide range of solar distances over the course of the mission. The direct incident solar flux varies from two times that at the Earth during inner solar system flight at Venus orbit ranges to ~100th that at the Earth during the mission in the Saturn system.

Operation with the SEP stage will involve attitude restrictions dictated by solar array illumination and thrust vector requirements. The SEP stage is operational from early in the trajectory, including at the Venus solar ranges, out to a maximum range of ~2 AU.

Venus Planetary Flyby

The Venus gravity assist flyby will impose the Venus IR thermal load for a short period in addition to direct solar incident energy on the Flight System. The conceptual design would protect the Flight System from both these sources by using a combination of specialized shielding and thermal surfaces, including use of the montgolfière heat shield and the large 4 m HGA to provide shading of the Flight System. Use of the montgolfière heat shield in this manner has the added benefit of providing shade to its own RPS heat rejection radiators as well. This combination of approaches will ensure thermal protection that can accommodate the range of attitudes that may be required by the SEP trajectory.

Electrical Power Consumption

The science mission takes place within the Saturn system at a distance of 9.1 AU from the Sun. At this range the electrical power will be provided by ASRGs and power consumption is to be minimized to limit the number of ASRG units required. The thermal control subsystem uses RHUs and ASRG waste heat to the maximum extent possible to minimize electrical power required for heaters.

Support Instrument Requirements

Several instruments for this mission require cold systems with temperature levels of 70 to ~170 K. The instrument will provide the cooling technology required, and the spacecraft thermal control subsystem will provide any shielding required to block thermal energy sources from the spacecraft.

In Situ Element Thermal Support

Two *in situ* elements are carried on the Flight System for the Baseline mission. The thermal control subsystem will provide a temperature controlled thermally isolated interface to support these elements. Adequate cooling during final integration to the orbiter, transportation, and on the launch pad will be provided by GSE air conditioning units (§4.4.6)

4.4.3.2.1 Thermal Control Subsystem Design

Spacecraft Bus

The spacecraft bus includes the C&DH, ACS, Power, Propulsion, and Telecom subsystems in addition to the SEP stage (**Figure 4.4-11**). The bus uses MLI, thermal surfaces, thermal conduction control, electrical heaters, and RHUs, both fixed and variable, to keep the spacecraft bus elements within specified temperature limits. The spacecraft thermal control subsystem provides thermal control for the shunt radiator of the Power subsystem using RHUs to keep it above its minimum electric element temperatures. The shunt radiator will be thermally isolated from the spacecraft when in use. It operates at a relatively high temperature (100°C a safe upper operational temperature for the resistors) and is located on the spacecraft body such that it has a clear view to space, and is away from low temperature hardware and instruments.

The Telecom subsystem is a separate unit, and consists of a 4 m diameter antenna, with all electronic parts mounted on a support structure on the back of the antenna. Thermal control for the Telecom subsystem uses the above elements, including RHUs, as well as a thermal louver/radiator to account for the large variation in thermal dissipation resulting from its duty cycle.

Propulsion Module

The propulsion module consists of propellant tanks, structure, and propulsion elements mounted in and on the propulsion module structure. This module uses the waste heat from three of the ASRGs to keep the propellant, tanks, lines, and valves safely above the

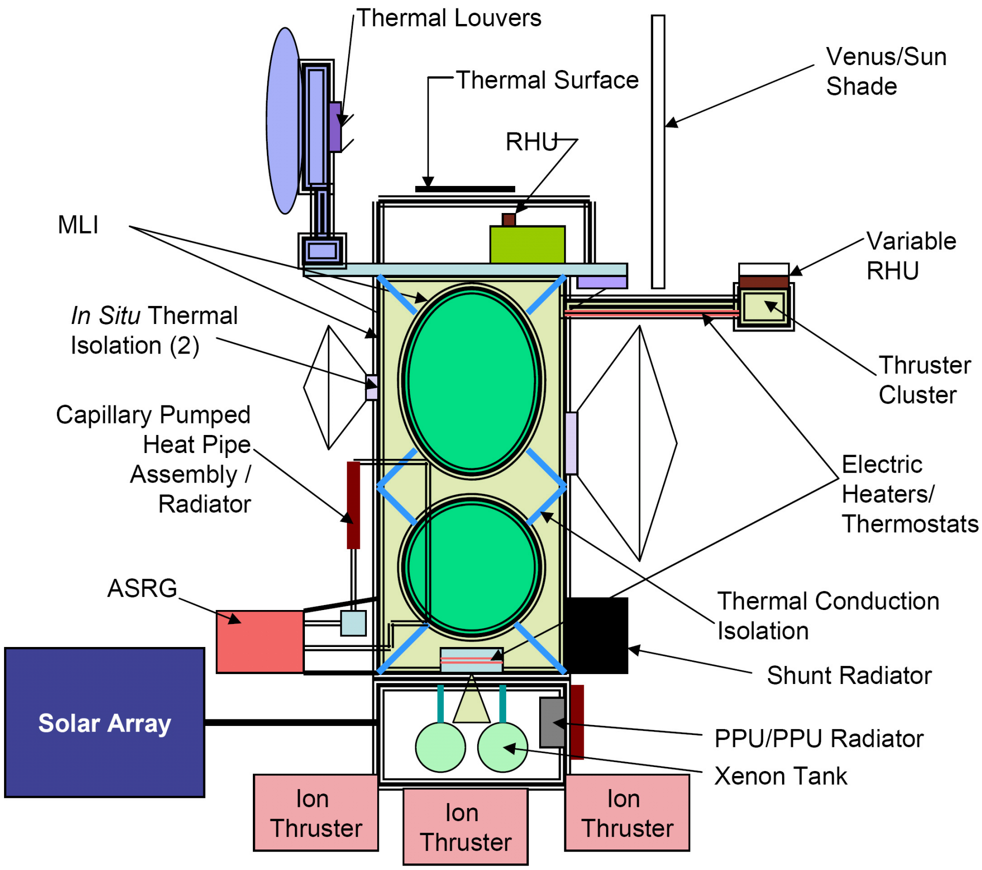


Figure 4.4-11. *Thermal functional block diagram.*

freezing point. The relatively low temperature (~70°C vs. ~170°C for an MMRTG) ASRG waste heat is utilized through incorporation of a capillary pumped loop system which includes thermal transfer panels, capillary loops, a control system and a thermal radiator. The capillary pumped heat pipes have been used in previous flight systems. Engineering development will be required for this design, but the individual elements have flight experience. The ASRG design includes an option for fluid loop accommodation, and this feature will be used to couple the capillary pumped heat pipe (CPHP) elements to the ASRG. Analysis indicates that about 200 to 300 W are required to maintain the propulsion module within temperature limits. Each ASRG has about 350 W of waste heat available at 70°C, thus using three ASRGs with the CPHP system provides the thermal energy required with ample margin after losses. The propulsion module can be maintained within specified temperature limits with the waste heat from two ASRGs, thus the CPHP system can provide the thermal energy required even with a single capillary loop failure.

There are two areas where RHUs and ASRG waste heat cannot be used, necessitating electric heaters: the propellant lines and the main engine valve module.

Payload Interfaces

The spacecraft bus also supports the instrument and *in situ* payload interfaces, and will maintain these interface temperatures using MLI, thermal surfaces, thermal conduction control, and variable RHUs. Further, two instruments, HiRIS and TIRS, require cryogenic radiators and low-temperature elements, and the bus thermal control subsystem will provide thermal shields as required.

SEP Stage

The SEP stage consists of the stage support structure, three ion thrusters, xenon tanks and

lines, solar arrays, PPUs and PPU radiators. Electric heaters will be used on the SEP stage during the SEP attached flight, as the solar arrays provide ample electrical energy. The SEP stage will be jettisoned at about 2 AU.

ASRG

The ASRGs are mounted on thermally isolated structures. Given the low surface temperature of the ASRGs, thermal shields will not be needed to protect Flight System elements. Mounting of the three ASRGs used in the CPHP system is optimized for heat transfer to the propulsion subsystem. The CPHP system maintains thermal control of the cold side of the ASRGs, even in the case of a failed generator, allowing tight spacing of these three units to facilitate the pumped-loop system. The remaining two ASRGs are located individually on opposite sides of the spacecraft to maximize their radiator view to space.

4.4.3.3 Power Subsystem

The TSSM orbiter is an RPS-powered spacecraft with an unregulated, nominal 28 V DC main power bus (22–36 V DC). Energy storage is provided by dual eight-cell lithium-ion batteries. Power bus control is accomplished via shunt regulation using a 2-out-of-3 majority voted, pulse width modulated control scheme. The batteries are operated directly off the main power bus, with constant potential control for charging. Grounding is a balanced bus, with both high side and return floating from spacecraft chassis, providing enhanced fault tolerance. Pyros are fired directly off the main bus power with critical arm and enable switches in series with the fire circuits.

Five ASRGs are used, producing 150 W each at beginning of mission (BOM). Four ASRGs are used to provide baseline power and the fifth is carried as a spare. Thus the spacecraft has 750 W available at BOM. Failure of a single ASRG would reduce the BOM power to 600 W. Each ASRG contains two general purpose heat sources (GPHSs), with a nominal BOM heat production of 500 W of thermal energy. ^{238}Pu decay heat drives a Stirling engine connected to a linear alternator producing AC power at about 102 Hz. Two Stirling engines, each with its own GPHS module, are incorporated in an ASRG. The two engines are mounted back-to-back as shown in **Figure 4.4-12**. An electronic controller is included in the ASRG to perform stroke control to synchronize the two pistons and minimize vibration. The controller also rectifies and conditions the AC square wave to provide a nominal 28 Vdc power output. Radioactive decay reduces heat available at a rate of ~0.8% per year, with no electrical or mechanical degradation assumed, resulting in a degradation of electrical power output at the same rate. End of Mission (EOM)

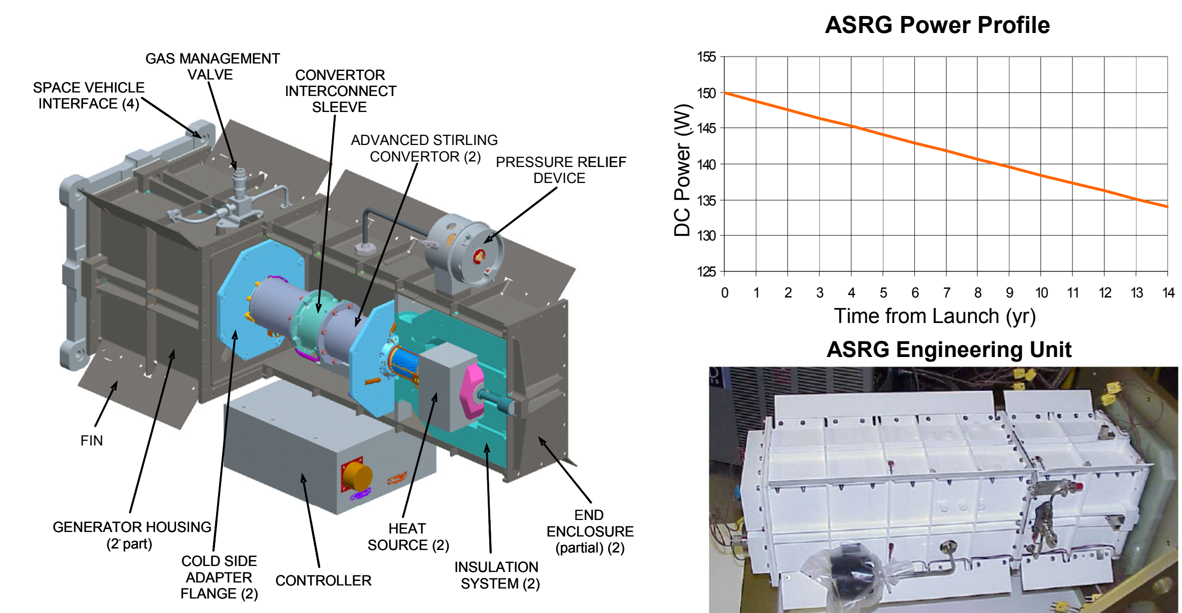


Figure 4.4-12. *ASRG characteristics.*

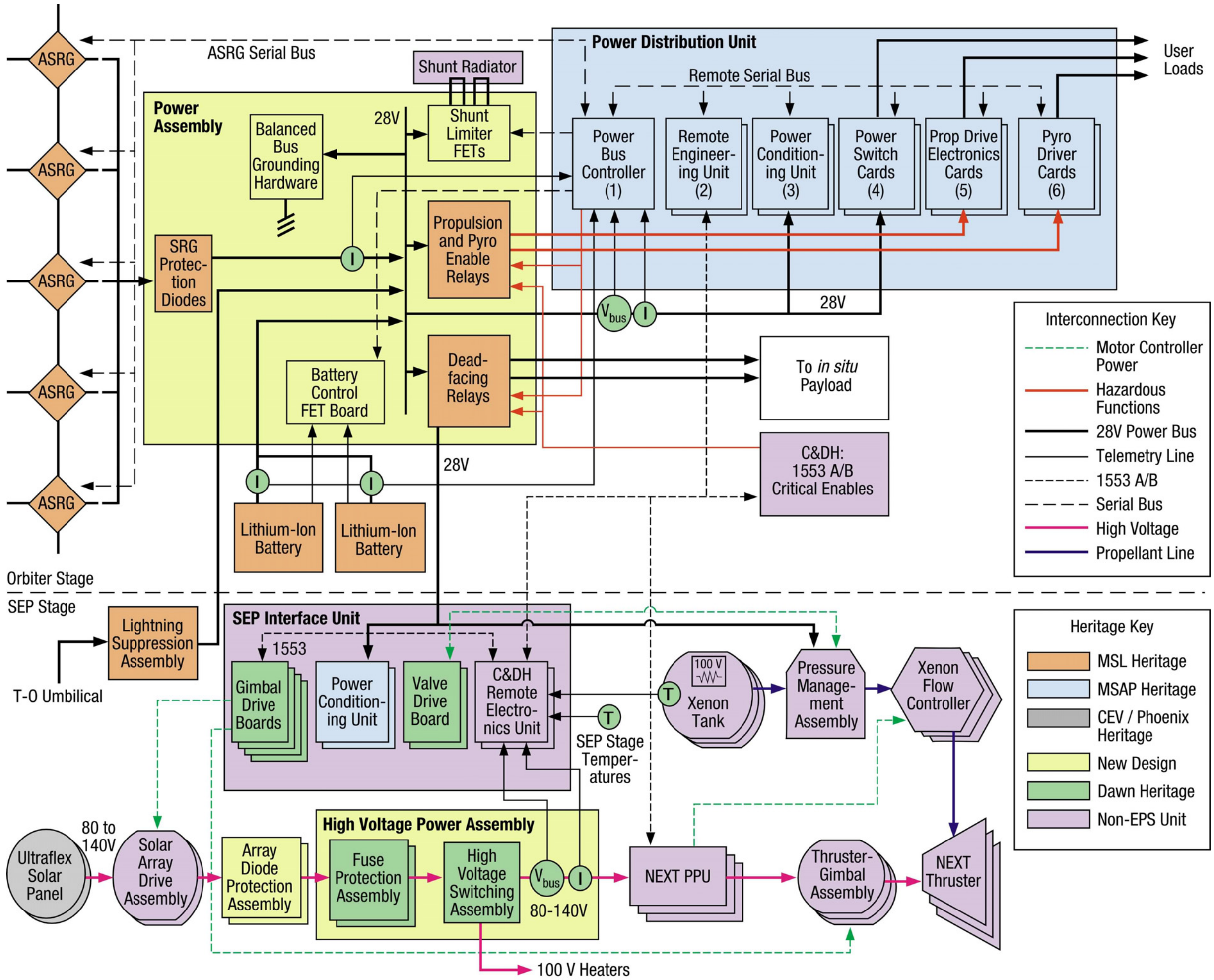


Figure 4.4-13. *Power subsystem block diagram.*

power available to the TSSM orbiter is estimated to be about 135 W per ASRG, resulting in ~540 W available to the spacecraft assuming four available units. Each ASRG has a CBE mass of 20.2 kg, and is also assumed to carry a spacecraft adapter at a mass of 1.2 kg.

A block diagram of the power subsystem is presented in **Figure 4.4-13**. The power electronics approach is to leverage all developments from JPL's multi-mission system architecture platform (MSAP) effort. As with all MSAP-based architectures, there are mission-specific functions not provided to the program requiring development. The power electronics suite is composed of two assemblies, the power distribution unit (PDU) and the power assembly (PA).

The PDU provides switching for general purpose, propulsion, and pyro loads. All loads switching is on both high and return side field effect transistor (FETs). The fault-containment region size for this architecture is at the board level, providing a significantly higher level of reliability compared to conventional dual-string architectures. The independent high and low side switches are commanded by separate digital command FPGAs. This prevents a command failure from causing a load switching failure. These boards are cross-strapped to redundant remote serial buses (RSBs) for commanding and housekeeping power. Main power bus sense and control signal generation is also accomplished in the PDU. Communication from the C&DH to the Power subsystem is via redundant 1553 buses, and within the PDU through remote serial bus. All of these functions are planned for MSAP development,

providing heritage to the TSSM orbiter PDU development.

The TSSM orbiter mission-specific PA contains functions that are packaged into a slice configuration, instead of the board-in-chassis method used in the PDU. This aids in packaging of items such as the main power bus junction, relays mounted in shock isolation trays, power FETs mounted on heat sinks, current sensing hardware, etc. The battery cell bypass FET functions are also found in the PA, with sense and control coming from the PDU as described above. Communications into and out of the PA are via discrete transistor transistor logic (TTL) level lines. A lightning suppression assembly is required for the launch support connections.

For energy storage, two redundant 25 A-hr eight-cell prismatic lithium-ion batteries are assumed, with a complete mission possible with a one-battery-failed state, and JPL design rules in effect for DOD (40% maximum). The range safety-required battery control and monitoring circuits are included in the PA. Sizing of the batteries is linked to science and telecom sequencing, as the batteries' primary function is load leveling in the nuclear powered application. They have additional roles of providing a low impedance source on the main power bus to stabilize voltage during load transients, such as pyro actuation.

SEP Stage Support

Design of the SEP stage, including a discussion of the power subsystem elements unique to that stage, is presented in §4.4.4.2. The power subsystem interfaces from the orbiter to the SEP stage are simple and narrowly defined. During the launch phase, the xenon tank pressures and temperatures are available to the orbiter via the SEP interface unit (SIU) 1553 interface. This requires the orbiter to supply 28 V power to the SIU and pressure management assembly (PMA) from the orbiter via dead-facing relays. During this phase the high voltage bus is not powered. After solar array deployment and throughout the thrusting phase, solar arrays power the electric propulsion components via the high voltage bus. High voltage bus power control is done by selecting throttle points in the PPU via the C&DH interface. When SEP thrusting is complete, the SEP stage is powered off, isolated electrically from the orbiter and jettisoned.

4.4.3.4 Telecom Subsystem

The TSSM Telecom subsystem provides high rate Ka-band playback of science data and engineering telemetry at Earth ranges up to 10.1 AU, robust and reliable uplink at X-band throughout all mission phases, reliable downlink during critical events such as SOI and TOI, and two-way Doppler and ranging data at both X and Ka-band for gravity science and navigation. An ultrastable oscillator (USO) will provide a high stability one-way reference for radio science (e.g., occultations). In addition, the subsystem will provide an X-band RF link for both commanding and reception of science data from the *in situ* elements.

There are two bi-directional links between the spacecraft and Earth: one at Ka-band and one at X-band. A block diagram of the Telecom subsystem is shown in **Figure 4.4-14**. X-band will be used for inner cruise and emergency communications. Ka-band will be used for high-rate data return during the science phases.

The Universal Space Transponder (UST), currently under development at JPL as the next generation deep space transponder, was selected for this mission for a number of reasons. The UST consists of a reprogrammable baseband processor, which is link frequency independent, as well as the frequency dependent circuit slices which support the RF processing functions. More than one set of circuit slices can be connected to the baseband processor, thus enabling simultaneous operation in more than one frequency band.

The UST brings significant flexibility to the TSSM Telecom subsystem by combining in a single unit the capabilities for telemetry downlink at both Ka-band and X-band, as well as providing an integral Ka-band translator which will allow for a Ka-band downlink coherent with a Ka-band carrier uplink for radio science. In addition its ability to support multiple simultaneous frequency bands allows accommodation of the *in situ* relay transceiver function without the need for additional hardware.

The key hardware elements of the Telecom subsystem are:

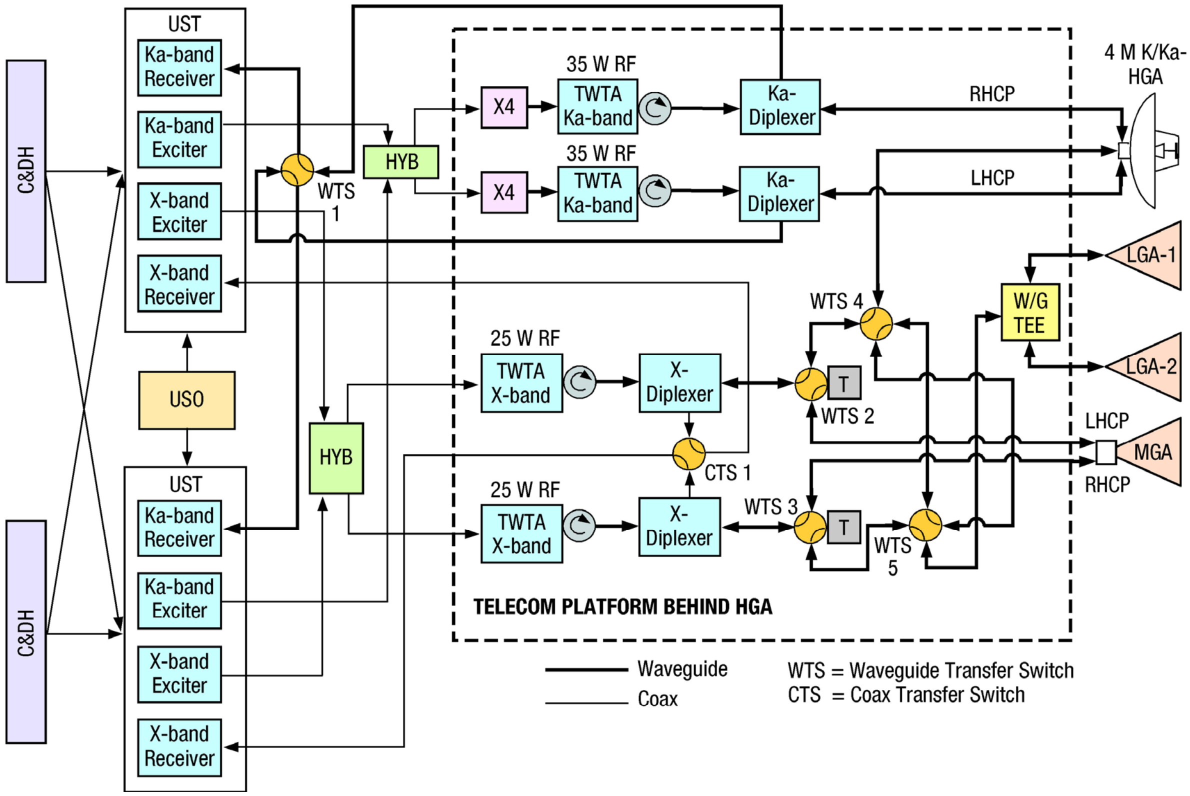


Figure 4.4-14. *Telecom subsystem block diagram.*

- Two USTs, which operate bi-directional DTE links at Ka-band and X-band
- The UST also works as a relay transceiver, which is used to support the relay link with the *in situ* elements
- Two cross-strapped Ka-band 35 W RF travelling wave tube amplifiers (TWTAs)
- Two cross-strapped X-band 25 W RF TWTAs
- 4 m diameter HGA
- 22 dBi medium gain antenna (MGA) for emergency comm. at max distance
- Two low gain antennas (LGAs) for 4 pi steradian coverage
- USO

Equipment for Support of Radio Science/Gravity Science

The UST is equipped with both X-band and Ka-band translators that will turn around the uplink signal provided by the DSN ground station at a fixed ratio. The two-way coherent downlink carrier received at the 34 m beam waveguide (BWG) antenna allows for precise Doppler measurements necessary to meet the Gravity Science requirements as described in §4.2.2.7. The JPL Frequency Standards and Timing lab will be used to validate and characterize the Allan Variance performance of the USTs.

Radio science occultation experiments are enabled by an oven-controlled USO which provides a stable frequency for the one-way downlink carrier to the DSN station. The USO will provide a reference that has Allan Variance of 10^{-13} at integration times of 10 to 100 s.

Interplanetary Cruise

The TSSM orbiter will reach the Saturnian system with support of a SEP stage and a EVEE gravity assist trajectory. Communication with the ground station during these gravity assist events will occur via the two LGAs pointed opposite each other to provide 4 pi steradian coverage.

The spacecraft will spend nine years from launch to SOI. During this period communication links will be closed using a combination of the LGA, MGA, and HGA antennas. Re-

view of the link budgets show that a data rate greater than 10 bps can be maintained throughout the Interplanetary Cruise Phase.

Critical Event Coverage

The spacecraft will encounter multiple mission critical events throughout the approach and science/orbit phases of the mission. The project has preliminarily defined the following as critical events: SOI, TOI, montgolfière release, montgolfière entry, descent and inflation (EDI), lander release, and lander entry, descent, and landing (EDL). The main engine will be used to reduce velocity for both SOI and TOI; during these events it is assumed the HGA will not be available and the LGAs will be used to maintain X-band downlink through 70 m DSN stations. During the monitoring of the EDI/EDL events for the *in situ* elements, the spacecraft will use the HGA/MGA to track the vehicles thus making the HGA unavailable for communication with the Earth. Orbiter communication with the ground could be maintained via carrier tones through the LGAs to a DSN 34 m array.

Saturn Tour Phase

The TSSM will be capable of maintaining >140 kbps downlink data rate to a 34 m BWG antenna at Ka-band via the HGA at up to 10 AU with a 3 dB margin. The downlink data rate capability improves as a function of station elevation angle (see design control table in **Table C.5-1**). Commanding capability to the orbiter is greater than 6 dB over 2 kbps at X-band from a 34 m BWG station. All commands sent to TSSM will be via the X-band uplink from the DSN stations. In the event of spacecraft safemode entry, the spacecraft will be oriented such that the HGA/MGA are sun-pointed. At maximum range, assuming a 7 degree sun-probe-earth (SPE) angle, the MGA antenna will be used to communicate at 10 bps to a 70 m ground station at X-band.

Two-way Doppler and ranging data will be collected during all data passes at X-band, and will be supplemented with Ka-band ranging and Doppler. In addition to Ka Up/Ka Down and X Up/X Down, the UST will also include an X Up/Ka Down translator.

In Situ Links

TSSM will carry two *in situ* elements for delivery to Titan; a short-lived surface lander lasting 9 hours, and a montgolfière aerial vehicle with a 6 month prime mission. Each of the elements will be released on approach maneuvers to Titan. The TSSM orbiter will act as the relay link between both *in situ* elements and the Earth. The TSSM orbiter will track each of the *in situ* elements during the critical EDI for the montgolfière, and EDL for the lander.

The montgolfière will be equipped with a steerable 0.5 m dish that will track the orbiter and a 25 W transmitter. The HGA on TSSM will be used to send commands and receive science data from the montgolfière at up to the 4,000,000 km maximum expected range. The orbiter will provide a carrier beacon that will allow the montgolfière aerial vehicle to locate and track the orbiter during relay. Nominal relay link data rates are 2 kbps at max range, with a link capability up to 1 Mbps at closest approach during Titan flybys.

For the lander element, the TSSM HGA will be used to track the asset during EDL; science playback will begin during descent. The lander has an X-band LGA and an 8 W transmitter. Unlike the montgolfière link, the lander link is one-way only. The data rate will start at 2 kbps at a max range of 87,000 km, and will increase to as high as 1 Mbps at closest approach. Both *in situ* elements will be on the reverse frequency plan (emulating a DSN station) enabling communication with the TSSM orbiter's UST. *In situ* to orbiter link rates are pictured in **Figure C.5-1**.

At ranges over 500,000 km, the footprint of the X-band 3dB beamwidth (0.3 deg) is a disk the size of Titan. At ranges greater than 500,000 km the TSSM will point at the moon in order to send instructions to and receive data from the montgolfière aerial vehicle. Under 500,000 km, the TSSM orbiter will implement a closed loop tracking system in order to accurately point the HGA to the *in situ* element. A dual-axis peak scan algorithm similar to the method employed by Voyager will be used to establish and maintain pointing accuracy necessary to support the relay link. This same scanning algorithm will be used during the critical EDI and EDL phases of the *in situ* elements.

4.4.3.5 Command and Data Handling Subsystem

The Command and Data Handling (C&DH) Subsystem for the TSSM is based on the Multi-Mission System Architectural Platform (MSAP) architecture (**Figure 4.4-15**) and uses a block-redundant flight computer to perform Flight System processing and control. The dual string C&DH subsystem includes:

- RAD750 Processor with 128 MB of rad-hard SRAM
- System Memory Card (SMC) card, with dual string arbitration capability, incorporates 1.75 Gb of Flash, 32 Gb of SDRAM.
- MSAP Telecom Interface (MTIF) with four radio interfaces and dual string arbitration capability
- MSAP System Interface Assembly with four ICC/ITC ports and 2 UART ports
- Compute Element Power Converter Unit (CEPCU) with support for the secondary voltages required by the other cards in the Compute Element chassis
- MSAP Remote Engineering Unit (MREU) utilizing the Remote Serial Bus to interface with low data rate instruments
- Custom Card (CC) with digital and analog interfaces needed to support the motor drive electronics as well as the Analog Sun Sensors.
- Housekeeping Power Converter Unit (HPCU) with support for the secondary voltages required by the MREU and the CC

The C&DH uses three primary paths to interface with the subsystems and components that it supports. The first of these is the arbitration interface found in the MTIF and the SMC

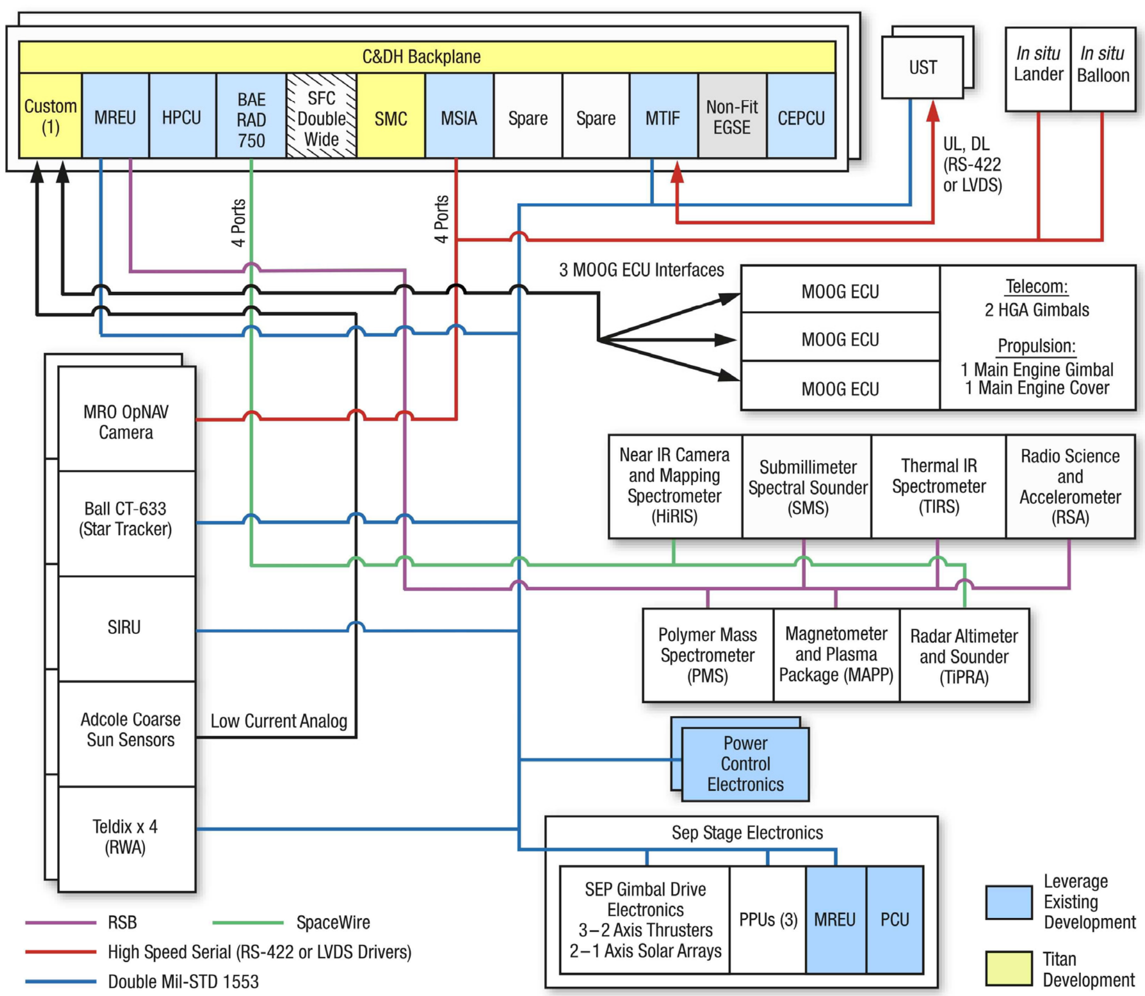


Figure 4.4-15. *C&DH block diagram.*

that allows the C&DH to support one of three redundant string readiness states: cold, warm or hot. These states will be defined in more detail in the Fault Tolerance section (see below). The second of the primary paths is the 1553 bus which is used for communication between the two C&DH strings and for communication with spacecraft peripherals that use a 1553 interface. The third path is the Remote Serial Bus (RSB), which is a 1 Mbps multi drop serial bus that is used within the C&DH subsystem to interface to the low data rate instruments. This is the same type of bus that will be used to interface with the power cards.

C&DH Card Descriptions

The spacecraft flight computer is a RAD750 processor running at 132 MHz with 128 MB of SRAM. It provides four SpaceWire ports capable of supporting up to 200 Mbps each that will be used to interface with two Titan instruments, the HiRIS and TiPRA.

The SMC provides the data storage, both non-volatile and volatile memory, needed to support engineering and science data. The SMC provides 32 Gb of useable SDRAM along with 1.75 Gb of non-volatile flash memory.

The MTIF houses the 1553 bus controller which is used in conjunction with flight software (FSW) to manage the 1553 devices found throughout the spacecraft. The MTIF contains the fault detection unit which is used for dual-string arbitration as well as four telecommunication interface ports that support several types of radios. Lastly, the MTIF also houses the Ground Support Equipment (GSE) interface, which includes T-Zero functionality and the LV interface, used to receive downlink from the spacecraft before launch vehicle separation.

The MSIA provides the C&DH subsystem with two types of point to point interfaces that can be used to communicate with instruments or other devices outside of the C&DH. The MSIA contains two UART channels (RS-422), each of which can handle up to a 2 Mbps data rate. It also contains four ICC/ITC channels (RS-422 or LVDS) which can handle up to an 8 Mbps data rate on each channel simultaneously. These interfaces are being used to communicate with the optical navigation cameras as well as providing interfaces for the two *in situ* elements while they are attached to the orbiter.

The MTIF uses the 1553 bus connection to communicate with the MREU. The MREU is the primary interface to the majority of the Titan instruments, the reason being that the majority of the instruments have data rates low enough to be allowed to communicate on the Remote Serial Bus while also taking advantage of the fact that this bus consumes less power than the 1553 bus, approximately a 1:5 ratio in power savings. The MREU also has the capability to sample up to 118 analog sensors which include 52 platinum resistor thermometers (PRTs), 16 temperature sensors and 48 differential analog voltage measurements. The components needed to support wakeup and shutdown functionality, (used when the backup string configuration is off), are located here. These are items such as the mission and alarm clocks, used for syncing with the spacecraft clock provided by the timing unit on the MTIF and for shutting down the backup unit when desired.

The Custom Card (CC) provides the C&DH subsystem with the capability to control the motor electronics that drive the gimbals located throughout the system. Since the electronics being used are, in particular, the Moog Electronics Control Units (ECU), this card will provide the digital command interface to the ECUs and the analog telemetry interface from the ECUs. The analog sun sensors require an analog interface as well, and so this was also placed on this card. Telemetry from the CC will be passed over the MREU's RSB to the MREU and then over to the flight computer via the 1553 connection between the MREU and the MTIF.

Both the CEPCU and HPCU designs will be heavily derived from the MSL PCU designs. These PCUs provide the set of secondary voltages that are required by the cards on the cPCI backplane as well as the voltages needed to operate the MREU and Custom Card.

Interfaces to Science Payload

Table 4.4-8 shows the list of planning payload instruments along with their associated data rates to the C&DH subsystem. Of the science instruments, the HiRIS and TiPRA require the use of a high-speed instrument

Table 4.4-8. Instrument data rates and interfaces.

Instrument Name	Max Data Rate Output to C&DH (kbps)	Interface
HiRIS	40,000	SpaceWire
MAPP Magnetometer	4	RSB
MAPP Spectrometer	5	RSB
MAPP Probe and Plasma	10	RSB
TIRS	20	RSB
PMS	10	RSB
TiPRA	20,000	SpaceWire
SMS	15	RSB
RSA	1	RSB

serial interface. The aggregate data rate of the remaining instruments totals less than 150 kbps, and can therefore be accommodated by the RSB.

The protocol of the Mars Science Laboratory Project Instrument Standard Electrical and Interface Specification will be adopted for the LVDS interface. The MSL Remote Serial Bus Specification will be adopted for the instruments on that bus.

Interfaces to ACS

Table 4.4-9 shows the list of the ACS components along with the interface being used to communicate with the C&DH subsystem. The reaction wheels, star trackers and SIRUs all have 1553 interfaces. The MRO OpNav camera uses an LVDS interface and can therefore be placed on a point-to-point interface channel provided by the MSIA. As discussed previously, the ECUs and the sun sensors have digital and analog interfaces that require the use of a custom built card and are therefore on located on the CC.

Interfaces to Telecom

The C&DH subsystem provides the Telecom subsystem with the 1553 bus used to communicate with the USTs. Uplink and downlink is handled through a dedicated LVDS or RS-422 interface. Specifically, the MTIF must support data rates as low as 10 bps to between 50 and 200 kbps.

C&DH Interfaces to Power

The only connection between the C&DH subsystem and the power subsystem is via the

Table 4.4-9. GNC component interfaces.

Instrument Name	Number of Interfaces Needed per String	Interface
Teldix Reaction Wheels	4	1553
Ball Star Trackers	1	1553
SIRU	1	1553
SEP Stage Gimbal Electronics	8	1553
Moog ECUs	3	Digital & Analog
Sun Sensor	4	Analog
MRO OpNav Cameras	1	LVDS

1553 bus to the Power subsystem's MREU. All power subsystem telemetry is collected over the Remote Serial Bus that is on the Power MREU and then communicated back to C&DH via this 1553 interface.

SEP Stage Support

C&DH provides an MREU that will be used to collect analog telemetry throughout the SEP stage. A corresponding PCU will accompany the MREU to provide the secondary voltages needed for proper operation. In addition, C&DH has reserved eight remote terminal 1553 connections for the gimbal drive electronic channels that reside in the SEP stage and three 1553 connection to support communications with the PPUs.

Fault Tolerance

The C&DH primary and backup strings can be used in three different modes: cold, warm or hot backup. Cold backup signifies that the redundant C&DH string is powered off, and for most of the Titan mission, this is the selected configuration. Warm backup signifies that the redundant string is on, able to respond to commands and send telemetry, and is ready to become the prime string if the fault detection unit (FDU) indicates that the prime string is not healthy. The hot backup state signifies that the redundant string is running in conjunction with the backup string and can take over spacecraft activities immediately if necessary. The current baseline is to use a cold backup redundant string; however, the C&DH architecture is capable of supporting a warm or hot backup if it is deemed necessary by further developments in the design.

All components on the 1553 and RSB are fully cross-strapped; failure of one interface does not require a string swap, the device can simply talk on the other bus. Fault tolerance is handled in two ways for point-to-point interfaces. The first is to allocate two point-to-point interfaces per string, instead of one, to a particular device in order to provide full cross-strapping capabilities. The second is to require that point-to-point interfaces that don't have a second interface on the same string have a redundant unit, but a string swap will be required if one side fails and that component is needed.

4.4.3.6 Attitude Control Subsystem

The TSSM Attitude Control Subsystem (ACS) is designed to support a three-axis controlled zero momentum spacecraft. The subsystem block diagram is shown in **Figure 4.4-16**. ACS uses reaction wheel assemblies (RWA) to control spacecraft attitude during all fine pointing scenarios. The reaction control system (RCS) consists of 16, 4.5 N hydrazine blow-down thrusters capable of providing three-axis control with redundant couples and vectored translation in the spacecraft X-Y plane. The RCS is used to unload excess RWA momentum and provide three-axis control during coarse pointing scenarios. Fifty kg of propellant is allocated for this. In addition the RCS can perform small ΔV maneuvers below the capability of the 890 N main engine as indicated in **Table 4.3-10**. The TSSM ACS utilizes high Cassini heritage algorithms using comparable ACS hardware and expects comparable flight performance. ACS sensors include redundant inertial measurement units (IMUs), star tracker assemblies (STAs), and coarse sun sensors (CSS). To provide redundancy and improve measurement accuracy the star trackers are not co-aligned. ACS flight hardware redundancy is provided by block redundancy and cross-strapping.

In addition to pointing, ACS is responsible for articulation of the HGA and the main engine, and for actuation of the main engine cover.

ACS functions begin by employing the IMU and RCS to null the residual spacecraft

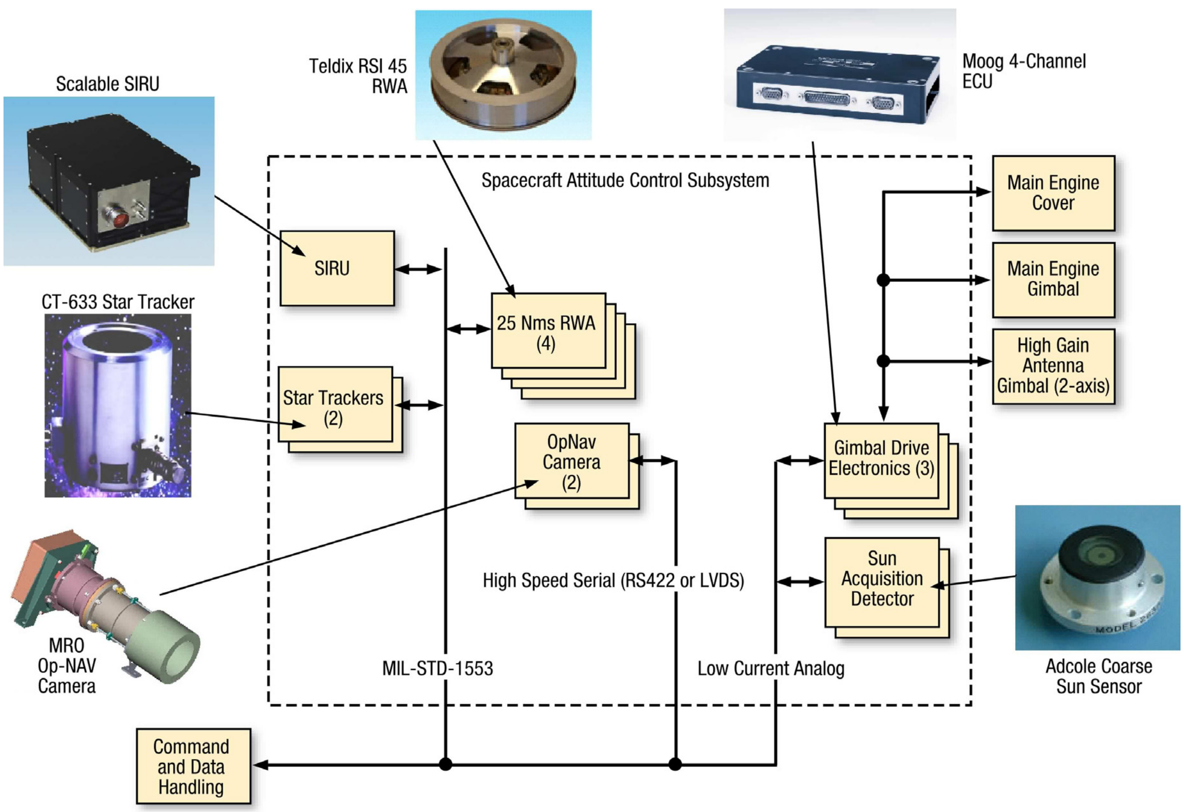


Figure 4.4-16. ACS block diagram.

tip-off rates imparted by separation from the launch vehicle upper stage after launch. Once accomplished the sun sensors are used to acquire the sun-line. ACS orients the spacecraft to a thermally safe sun-pointed attitude and begins to take stellar attitude updates. This process is employed by ACS following launch and any other time that attitude reinitialization is required.

During the first several years of the Interplanetary Cruise Phase solar electric propulsion (SEP) thrusters will be used. Each of the three SEP thrusters is mounted on a two-axis gimbal, providing pitch and yaw thrust vector control (TVC). During SEP thrusting, roll control is provided by RWAs. The RWAs will also be used to absorb torque imparted by the SEP thrusters about the thrust vector.

The two ESA-provided *in situ* elements would be released during the Saturn Tour Phase following the SOI burn. They would arrive at Titan on the first and second Titan flyby encounters (T1 and T2). ACS supports all *in situ* element release pointing and telecom relay requirements. RWAs will be used for a period of time prior to *in situ* element release to ensure minimal orbit perturbations. Optical navigation can also be employed to drive down *in situ* element orbit determination (OD) uncertainties. Due to the high target motion compensation (TMC) required during the *in situ* element relay tracking period, ACS will track the *in situ* elements by slewing the spacecraft with the RCS while maintaining a fixed HGA gimbal position.

Large maneuvers such as SOI and TOI are performed using the 890 N main engine. ACS performs thrust vector control via the 2-axis main engine gimbal, roll control is provided by RCS 4.5 N thrusters. Small maneuvers are performed via RCS (see **Table 4.3-10**) using 4 X- or Y-facing thrusters. The thrusters are off-pulsed to ensure zero net torque imparted over the maneuver due to the center of mass (CoM) not aligning with the thruster mechanical frame.

Following the TOI burn, ACS supports 60 days of aerobraking to reduce the highly elliptical orbit into a 1500 km circular orbit. During the Aerobraking Phase, the spacecraft flies through Titan's atmosphere in an aerodynamically stable attitude with the center of pressure (Cp) behind the center of mass (CoM). During this time the spacecraft flies with the –Z-axis into the ram direction and +Y-axis to nadir, with the HGA stowed near the launch configuration.

During the Aerobraking Phase of the mission the TSSM spacecraft will reach altitudes as low as 600 km which will provide excellent science opportunities for the polymer mass spectrometer (PMS) instrument. To avoid thruster plume impingement effects on PMS during aerobraking, ACS will operate with loose attitude control deadbands preventing rapid thruster pulses and will utilize only the aft four thruster clusters located on the opposite end of the orbiter from the PMS instrument. During the Aerobraking Phase attitude control provided by the RCS will be performed without couples; however, any thruster firing should be limited due to the aerodynamic stability of the aerobraking attitude.

After aerobraking, ACS maintains a science attitude for the Circular Orbit Phase of the mission. During this time the spacecraft flies with +Y-axis to ram and –X-axis to nadir. In this orientation the +Z axis is the cold side of the spacecraft. Although this attitude is not gravity gradient stabilized, the spacecraft maintains attitude near an unstable equilibrium and the gravity gradient torque is small.

Key Driving Requirements

Basebody pointing requirements on the TSSM orbiter are listed in **Table 4.4-10**.

The pointing knowledge requirement is driven by HGA pointing. The pointing control requirement is not directly required for HGA or science pointing objectives. ACS assumes tight control of the spacecraft body attitude in order to reduce undesirable interactions between the HGA and basebody controllers.

Table 4.4-10. *TSSM pointing requirements.*

Pointing Requirement	3-Axis Science	HGA Boresight	OpNav	Maneuver
Control	1.0 mrad (3σ, per-axis)	0.7 mrad (3σ, radial)	1.75 mrad (3σ, per-axis)	30 mrad (3σ, per-axis)
Knowledge	0.2 mrad (3σ, per-axis)	0.35 mrad (3σ, radial)	0.88 mrad (3σ, per-axis)	4 mrad (3σ, per-axis)
Stability	60 μrad/s (3σ, per-axis)	Not a Driver	2.4 μrad over 5 s	Not a Driver

The pointing stability requirement is driven by the optical navigation camera jitter requirements. ACS shall not allow jitter greater than 1/10 pixel in the optical navigation CCD during a 5 s exposure period.

ACS Flight Equipment

The ACS flight hardware and hardware commanded by ACS are discussed in the following paragraphs and include:

- Coarse sun sensors
- Ball CT-633 star trackers
- Northrop Grumman scalable SIRU inertial measurement unit
- Teldex RSI 45 reaction wheel assemblies
- Moog 2 and 4 channel electronic control units
- MRO heritage optical navigation cameras
- Dawn heritage gimbal drive electronics for SEP stage

ACS utilizes redundant sun sensor assemblies (SSAs) to facilitate safing recovery and attitude reinitialization. The ACS Baseline design includes redundant coarse sun sensors. These sun sensors are light and inexpensive with a wide FOV.

Precision stellar inertial attitude knowledge is provided by redundant star trackers. ACS Baseline design includes redundant Ball CT-633 star trackers. The CT-633 outputs quaternions which greatly reduce the star identification data volume.

The attitude estimate is propagated with the inertial measurement unit (IMU) between stellar inertial attitude updates, or when stellar attitude is unavailable. Pointing stability is not a significant ACS driver; the optical navigation camera is the only instrument that drives a jitter requirement. ACS Baseline design uses a single internally redundant Northrop Grumman scalable SIRU IMU. In addition to the rate information the IMU will provide three-axis acceleration measurements. The accelerometer resolution capability provided by the Allied Signal accelerometers is 0.01 μg.

ACS provides three-axis attitude control with three orthogonal RWAs with a fourth skewed backup RWA. The orthogonal RWAs (RWA-1, RWA-2, RWA-3) are arranged symmetrically with respect to the spacecraft Y-axis; the backup skew RWA spin vector is parallel to the spacecraft Y-axis.

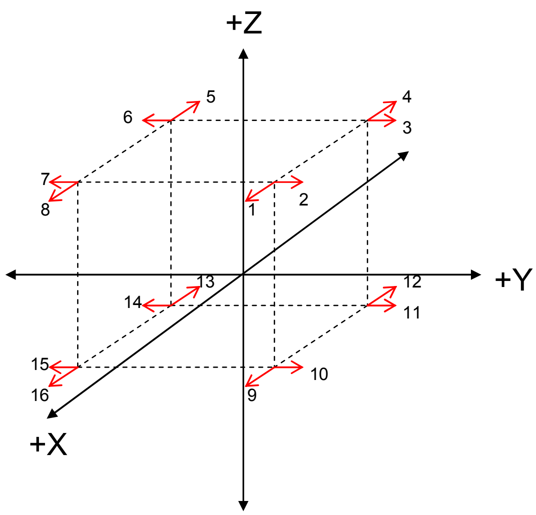
The dominant external torque acting on the TSSM spacecraft is the gravity gradient torque experienced in Titan orbit, acting along the spacecraft Y-axis. The RWAs are oriented to allow for symmetrical gravity gradient momentum absorption on each of the three prime RWAs, increasing the storage capability of the RWAs, which results in reduced total revolutions and increased robustness to a failed RWA.

RWA sizing is a balance between attitude control capability and unit mass and power. ACS selected RWAs with 25 Nms angular momentum storage capacity, which can support three days of continual operation without requiring a momentum unload or exceeding 50% of the storage capacity on any single wheel. ACS Baseline design includes four Teldix RSI 45, 25 Nms RWAs. The RSI 45 flywheel can be interchanged with a larger or smaller one if the 25 Nms angular momentum storage capacity is deemed inappropriate as the design progresses.

ACS provides gimbal and actuator driver electronics for the HGA two-axis gimbal, the two-axis main engine gimbal assemblies and the main engine cover actuator. ACS controls the four gimbals with two cross-strapped four-channel electronic control units. ACS Baseline design includes two Moog four-channel electronic control units (ECUs). The cover actuator is redundantly controlled by a single two-channel Moog ECU.

Optical navigation is important primarily to determine Enceladus ephemeris for the low-altitude Enceladus flybys. It can also be used to improve the reconstruction of *in situ* element release as was done for Huygens. ACS Baseline design includes redundant MRO build-to-print optical navigation cameras.

ACS utilizes 16 small RCS thrusters to perform RWA momentum management, execute small ΔV maneuvers, and control the spacecraft during loose pointing phases of the mission such as cruise. TSSM ACS thrusters use high heritage 4.5 N hydrazine blow-down thrusters. The TSSM thruster configuration (**Figure 4.4-17**) provides high control authority with five degree-of-freedom (DoF) control. The 16 thrusters are arranged in eight clusters of two thrusters each, with latch valve isolation for each cluster. The isolation strategy



Arrows denote plume direction

Figure 4.4-17. *ACS thruster orientation.*

guarantees that the loss of a single thruster or thruster cluster does not preclude ACS from providing three-axis control with couples.

ACS provides redundant gimbal drive electronics for the SEP stage. Four Dawn spacecraft gimbal drive electronics (GDE) are selected to support both the SEP engine gimbal actuation as well as the two single-axis solar array gimbals.

4.4.3.6.1 ACS Algorithms

Suspend Star Identification

Due to the number of large bright bodies in the Saturnian system, and the motion of the node during Titan orbit, star tracker placement that precludes bright bodies entering the FOV is not possible. The star trackers are body mounted, and the spacecraft body attitude is constrained by the science pointing objectives, precluding star tracker-friendly attitudes in Titan orbit. During the Titan Orbit Phase, Saturn will have an angular diameter of approximately 6°, while the rings will have an angular diameter of approximately 13°. These large bright bodies will pass through the optical FOV of the star tracker during periods of the orbit and can potentially cause blooming difficulties for the star tracker optics.

ACS considered two schemes to mitigate the star identification concerns regarding the bright bodies at Titan orbit. One solution is to swap to the backup star tracker during periods of time when the orbital geometry makes the prime star tracker unfavorable. It is likely that another swap(s) will be required as the orbit precession continues. This violates the JPL design principals for power cycling hardware. Another solution is to implement flight software logic to suspend star identification as is performed on Cassini. Stellar attitude updates are suspended during a period of time and attitude is propagated on gyros alone.

The algorithms to suspend star identification have been successfully implemented on the Cassini spacecraft which experiences star id suspensions on significantly longer time scales than those predicted for TSSM. This capability is included in the TSSM flight software.

Thrust Vector Control via Main Engine Gimbal

ACS is responsible for thrust vector control (TVC) during main engine maneuvers. The large shifts in CoM for the TSSM spacecraft, most notably the shifts following the *in situ* element release, necessitate a gimbaled main engine. ACS performs TVC about the spacecraft X and Y-axis via a Cassini heritage two-axis gimbal, TVC about the spacecraft Z-axis is performed via 4.5 N RCS thrusters. ACS TVC algorithms utilize high Cassini heritage.

HGA Boresight Open Loop Pointing

The most stringent of the ACS pointing requirements for the TSSM mission is the HGA boresight pointing. The HGA is mounted on a MRO heritage two-axis gimbal. ACS is required to point the HGA boresight to within ±0.7 mrad (3σ, radial).

Uncalibrated and calibrated HGA pointing error budgets were constructed on the basis of flight performance from the Cassini and MRO spacecraft. It should be noted that the HGA pointing requirements are tighter than the requirements for either Cassini or MRO. The MRO HGA pointing error budget was modified to account for to the high heritage of the TSSM HGA gimbal assembly. In general, terms referring to spacecraft body pointing capabilities use Cassini heritage/flight performance values, while terms referring to the gimbaled HGA pointing capabilities use MRO heritage/flight performance values.

Table 4.4-11. *Calibrated HGA pointing error budget.*

Calibrated HGA Pointing Error Budget			
Error Category	Error Term	TSSM Allocation (mrad)	MRO Allocation (mrad)
Spacecraft Pointing Knowledge		**0.15**	**1.00**
	Spacecraft pointing knowledge	0.15	1.00
HGA Control Errors		**0.30**	**1.00**
	Control Loop cmd and track error (incl flex, slosh, arrays, inst., environ, dist)	0.30	1.00
HGA Knowledge Errors		**0.51**	**1.11**
	Position encoded resolution	0.20	0.30
	Encoder zero refernece knowledge	0.10	0.25
	HGA electrical to mechanical boresight knowledge error	0.10	0.50
	HGA mechanical boresight to AD reference alignment error	0.04	0.40
	One-g measurement error	0.04	0.40
	Optical alignment cube tolerance	0.04	0.10
	Launch shifts	0.04	0.35
	Moisture/outgassing	0.04	0.20
	Elastic deformation (AD reference to boresight) w/ dist.	0.20	0.20
	Thermal deformation (AD reference to HGA base)	0.30	0.45
	Thermal deformation (dish-HGA base to boresight)	0.25	0.30
Ephemeris Errors		**0.21**	**0.21**
	Earth ephemeris knowledge	0.05	0.05
	Representation errors	0.06	0.06
	Clock errors	0.19	0.19
Margin		**0.28**	**-**
	Total (3-sigma, radial)	**0.70**	**1.81**

It is assumed that all the error sources in the error budget presented in **Table 4.4-11** are uncorrelated, and thus it is appropriate to use the square root of the sum of the squares (RSS) for each error source. In order to meet the pointing requirements in-flight calibrations will occur during interplanetary cruise and Saturn orbit. During the in-flight calibrations the HGA will return to the known launch position in order to reduce gimbal position and control related error sources (encoder position resolution, control loop, zero reference knowledge, etc.).

In-flight calibrations will greatly reduce the HGA knowledge errors. The following in-flight calibrations will be performed: star trackers to attitude determination (AD) reference, electrical to mechanical HGA boresight, and AD reference to HGA base misalignment. Thermal deformation during eclipse periods will also be characterized.

While the TSSM HGA pointing requirements are tighter than either the Cassini or the MRO HGA pointing requirements the error budget is achievable. The post-calibration HGA pointing performance (including margin) is estimated to be to be ±0.7 mrad (3-sigma, radial), which corresponds to ~0.5 dB loss.

4.4.3.7 Propulsion Subsystem

The leading design drivers for the propulsion subsystem are the mission duration and the required ΔV for the mission. The high ΔV requirement results in high engine throughput, many engine start-ups, and associated valve cycle usage. This, in turn led to the selection of a robust 890 N main engine and thrusters with good qualification margins and an extensive test history.

The primary thruster configuration requirement is the need to minimize residual ΔV during momentum wheel desaturations. When combined with a redundancy requirement, this resulted in a configuration of 16 thrusters located on the eight “corners” of the Flight System as illustrated in **Figure 4.4-17**.

The propulsion system (**Figure 4.4-18**) is a dual mode, bipropellant system using hydrazine (N_2H_4) fuel and nitrogen tetroxide (N_2O_4 or NTO) oxidizer. Approximately 2700 kg of propellant is carried. The N_2H_4 and N_2O_4 are used by the 890 N (200 lbf) bipropellant main

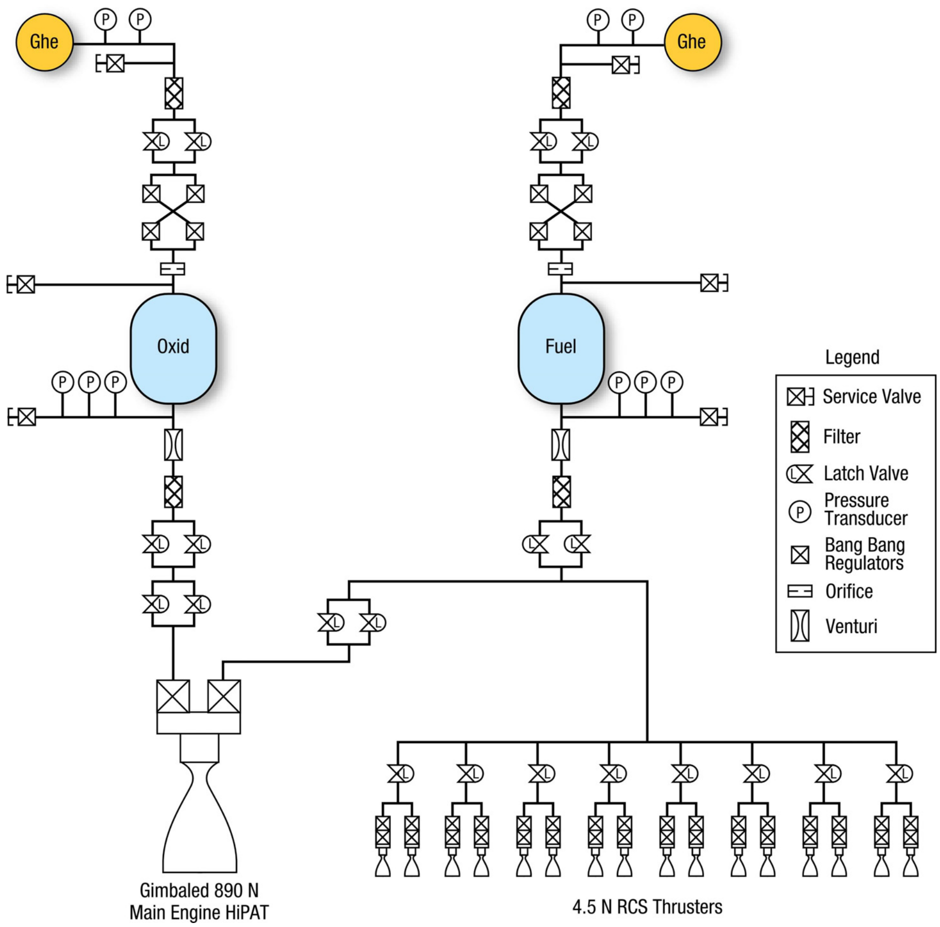


Figure 4.4-18. Propulsion block diagram.

engine. The hydrazine is also used by the monopropellant RCS thrusters.

The baseline for the main engine is a 890 N (200 lbf) thrust NTO/N_2H_4 bipropellant engine currently being developed by Aerojet, Redmond. The engine is a scaled-up version of their 450 N (100 lbf) class high performance liquid apogee thruster (HiPAT) engine.

Sixteen Aerojet 4.5 N (1 lbf) MR-111 thrusters (eight primary and eight redundant) are baselined to provide attitude control (e.g., three-axis limit cycle control, reaction wheel desaturations, Flight System turns, etc.) for the Flight System. In addition, the thrusters may be used for very small ΔV maneuvers.

TSSM will qualify composite overwrapped pressure vessels (COPV) for the propellant tanks. The COPV will have a thin (0.5 mm) commercially pure titanium (CPTi) liner for compatibility and hermetic sealing with an internal titanium surface tension expulsion device. This liner will be overwrapped with a composite consisting of an ultra-high strength carbon fiber in an epoxy matrix resin for pressure containment and structural loads. The tanks will be mounted using a composite skirt at the head-to-cylinder junction. The liner is subject to fracture control to preclude fracture or leakage. Design, manufacture, verification and safety of this COPV will be governed by ANSI/AIAA S-081-2000 which the NASA Headquarters Office of Safety and Mission Assurance has adopted (NPD 8710.5D).

The TSSM propellant tanks would be 1321 mm (52 in.) diameter. COPVs of 914 mm (36 in.) diameter using the same technology have flown several times on the A2100 spacecraft and a 1321 mm (52 in.) OD scaled up version has been baselined for the Orion Service Module propellant tanks. In addition, NASA/GSFC is currently qualifying a 1016 mm (40 in.) aluminum-lined COPV propellant

tank for the Global Precipitation Measurement Project. The tank manufacturer, ATK, has stated that they will provide the proposed tanks on a firm-fixed-price contract.

4.4.3.8 Flight Software

Highly reliable software for mission-critical applications is essential for this long-life mission. The flight software baseline uses a flight proven architecture implemented in accordance with JPL requirements for NASA Class B (non-human space rated) software development. JPL has established a set of institutional software development and acquisition policies and practices, as well as design principles that apply to mission-critical and mission-support software. These practices conform to the NASA Procedural Requirements for Software (NPR 7150.2) and are an integral part of the JPL FPP and DPP. All flight software will be developed in accordance with JPL institutional policies and practices for deep space missions, which include JPL's Software Development Requirements (D-23713) that address all CMMI process areas up to maturity level 3. Software identified as safety critical shall comply with safety critical requirements, regardless of software classification. Software safety criticality assessment, planning and management will be performed for all software including new, acquired, inherited, and legacy software and for supporting software tools. Software will be identified and documented as safety critical or not safety critical based upon a hazard analysis conducted prior to start of development activities.

The flight software will be written in the C language using the VxWorks operating system and will be organized in a layered architecture as shown in **Figure 4.4-19**. This architecture will be revisited in Phase A during the flight software architecture trady study.

The Baseline operating system abstraction layer will fully encapsulate VxWorks operating system functions and provide the following functions to the applications, services, device manager, and device driver layers:

- Inter-task messaging
- Task synchronization
- Task management

The Baseline device driver layer will interface directly with the hardware. The layer will contain drivers that provide control and data

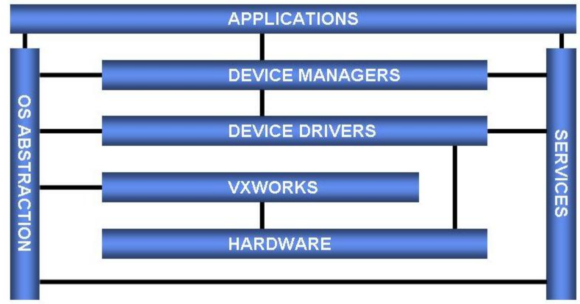


Figure 4.4-19. *Flight software architecture.*

abstractions to the device manager and services layers. The drivers will communicate with the hardware using the device-specific syntax. This layer will provide the following functions for each device:

- Convert control requests into lower level activities
- Manage data transfer between device managers and hardware
- Provide hardware device protocols that maintain the correct sequencing of requests, reject bad requests, prioritize valid requests, and inform device managers when requests are satisfied
- Monitor and maintain hardware states
- Monitor for events and faults
- Respond to interrupts
- Enable and disable correct interrupts at initialization
- Connect correct handlers to interrupts

The Baseline device manager layer will interface with the device drivers and will not be concerned with the hardware interface syntax. Instead, the layer will provide device operating semantics to the applications and services layers, allowing device managers to be reused independent of hardware interface syntax. This layer will provide the following functions for each device:

- Device management functions through interfaces to the device driver, including functions to configure, enable, disable, and reset hardware and instruments
- Software service and applications interfaces to process device and instrument control requests and wait for data from device drivers

The Baseline services layer will interface with the device managers, drivers, and OS abstraction layer, and provide common system services and system resource housekeeping functions throughout. This layer will include the following service functions:

- File system data storage and retrieval
- Science and engineering data management and compression
- Telemetry data collection, processing, packetization, and framing
- Event reporting
- Time services, including alarms and clock references
- Memory management, including scrubbing and defragmentation
- Event and time-based command sequencing engines
- Command dispatch
- Non-volatile parameter management

The Baseline application layer will interface with the services, device manager, and OS abstraction layers and provide high-level behaviors for implementing mission functions. This layer will include the following application functions:

- Uplink and downlink interfaces to the ground system and *in situ* payloads, including command receipt verification and validation
- High-level fault protection monitor and response behaviors that detect and recover from anomalies encountered during all phases of the mission, including launch, *in situ* element release, and Saturn orbit insertion
- Fault protection manager
- Flight software health monitor and self-tests
- Spacecraft mode and configuration managers
- Redundancy manager
- Flight software state manager
- Activity constraint manager
- Resource and activity arbiter
- Communication behavior manager
- Science behavior manager
- Instrument behaviors
- Guidance and control behaviors, including attitude estimation and control, solar array pointing, trajectory correction maneuver and electric propulsion control, momentum management, and HGA pointing

The Baseline flight software will incorporate the following functionality to reduce operations cost as recommended by the Mission Operations Lessons Learned Study for The Next Outer Planets Flagship (OPF) Mission (Holdridge et al. 2008, see Appendix K).

- Automated momentum management
- Onboard ephemeris based pointing
- Onboard file system, and pre-allocation of SSR memory resources by Ground Rules
- Automated file playback for downlink
- CFDP for telemetry, and automated retransmissions for data dropouts
- CFDP for command uplink

Most of the above functions have been implemented by previous JPL missions (namely Cassini and MSL), and their design, and in some cases implementation, can be directly inherited. CFDP automated retransmission will require new flight software development.

A large portion of the Baseline TSSM software will be inherited from the Multi-Mission System Architectural Platform (MSAP) development activity and MSL. The software will provide high test and operational flexibility to accommodate science and engineering needs, autonomous fault recovery, and in-flight software updates for the resolution of unforeseen situations. In addition to the flight software itself, other inherited products reduce development cost and risk. This includes documentation, and the development environment (configuration management, test harnesses, and scripts) for the inherited flight software functionality. Further, the MSAP simulation test environment includes simulation for the MSAP supported hardware. The Baseline operating system, sequencing, and fault protection engines will be inherited from MSL. Minimal effort is assumed for the adaptation of these specific products for TSSM. Inheritance reviews will be performed prior to the PDR to confirm the degree of commonality of the inherited components.

4.4.4 SEP Stage

The Solar Electric Propulsion (SEP) stage is based on the NEXT ion thruster technology and provides significant flight time and delivered mass benefits.

4.4.4.1 SEP Stage Configuration

The TSSM SEP stage is built around a custom launch vehicle adapter that provides the interface between the launch vehicle and the TSSM orbiter. The stage is powered by a pair of 7.5 kW Ultraflex solar array wings based on those currently under development for the Orion Crew Exploration Vehicle (CEV). These arrays power up to two simultaneously operating and independently gimbaled NEXT ion thrusters (Hoskins et al. 2007).

The stage includes three NEXT ion thrusters (**Figure 4.4-20**) and associated PPUs. A maximum of two ion thrusters are operated at a time, and the mission can be accomplished with just two of the three thrusters available. The third ion thruster/PPU string is used to make the ion propulsion system single-fault tolerant. The ion thrusters are fed by xenon stored in three composite overwrapped pressure vessels (COPVs) mounted inside the stage's cylindrical structure. The xenon flow rate is controlled by commercially available, flight-qualified feed system components.

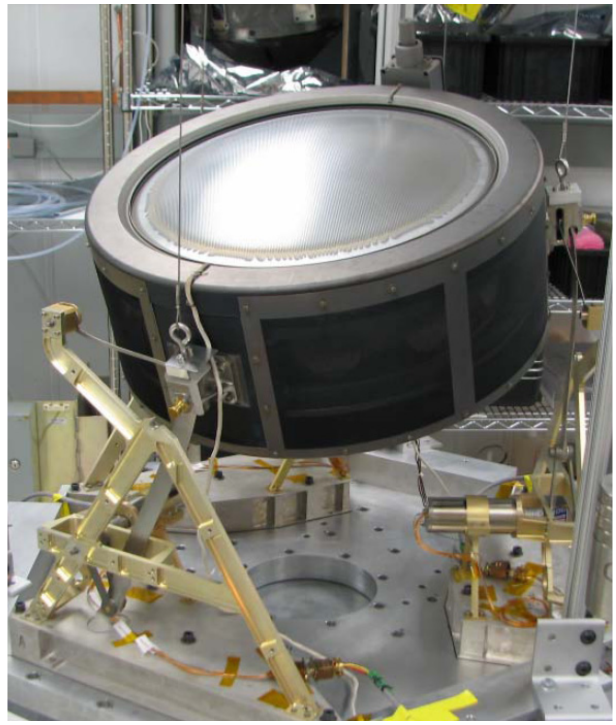


Figure 4.4-20. *NEXT thruster and gimbal.*

The configuration of the SEP stage mated with the Titan orbiter is shown both in the cruise configuration and in the stowed configuration in **Foldout 3** (**FO-3**). The large nozzle from the orbiter's bipropellant main engine extends into the SEP stage along the center line with plenty of clearance relative to the xenon tanks as shown in the figure in the lower left-hand corner of this foldout. Guide rails are used to guarantee that the SEP stage cannot contact the orbiter's chemical thruster nozzle during separation.

Each ion thruster is mounted on its own two-axis gimbal. The gimbals chosen for this design are the same as those used in the Dawn ion propulsion system and can easily accommodate the larger diameter of the NEXT thrusters relative to those used on Dawn. These gimbals have sufficient control authority to enable either single thruster operation or any combination of two-thruster operation. Most of the SEP-powered cruise thrusting is performed with two simultaneously operating thrusters. During these times the SEP system will be capable of providing full three-axis control of the Flight System under the command of the orbiter's attitude control system. The resulting total thrust vector for the two thrusters will nominally go through the center of mass of the spacecraft, although the individual thrust vectors from each thruster will not. Consequently, there is no cosine thrust loss associated with the operation of two thrusters. When only one ion thruster is operating the SEP system will be capable of providing pitch and yaw control for the Flight System. While the current plan is to operate the minimum number of ion thrusters whenever thrusting is required, the SEP stage has sufficient power to operate two thrusters at all times. Therefore, if roll control during single thruster operation becomes an issue, it could be solved by always operating two thrusters simultaneously with no change to the Flight System.

Thermal control of the SEP stage is accomplished through the use of large, light-weight radiators to reject waste heat from the PPUs during thrusting cruise, and 100 V heaters and blankets to maintain the desired temperatures of the other stage components. The High-Voltage Power Assembly (HVPA) distributes 100 V power from the solar arrays to the PPUs and to the thermostatically-controlled, 100 V heaters.

The thermal impact of the large solar arrays on the ASRGs is negligible. The design en-

sures ample clearance between the solar arrays and the orbiter in both the stowed and cruise configurations. Plume impingement from the RCS thrusters on the solar arrays has been taken into account in the layout and would not be a problem in either configuration. The stowed solar arrays easily fit within the launch vehicle shroud.

4.4.4.2 SEP Stage Components

The primary SEP stage structure is a 1.57 m (62 in.) diameter by 1.27 m (50 in) high cylinder. This structure takes the place of the launch vehicle adapter and provides the interface between the Atlas V 551 launch vehicle and the orbiter. This structure supports the entire wet mass of the orbiter as well as the wet mass of the SEP system.

All of the SEP stage components have either already been flown or are in advanced development. A development-model NEXT ion thruster is pictured in **FO-3** along with an engineering-model (EM) NEXT PPU. The NEXT thruster has successfully completed an environmental test program, including vibration and thermal-vacuum testing at levels enveloping what is needed for the TSSM SEP stage. A functional-model NEXT thruster is currently in an ongoing life test at Glenn Research Center (GRC); this test has demonstrated a propellant throughput of over 350 kg thus far. This life test is funded through the demonstration of a 450 kg throughput. Propellant mass throughput capabilities of just over 225 kg per thruster are required for the TSSM Baseline mission design. The useable NEXT thruster throughput capability is currently projected to be well over 480 kg per thruster. The EM PPU has demonstrated the ability to operate the NEXT thruster over its full throttle range.

The solar array is an upscaled version of the Ultraflex solar arrays successfully flown on Phoenix. The array consists of two wings of approximately 6 m diameter each populated with triple-junction GaAs cells. A photograph of a development-model wing is shown in **FO-3**. This size array is currently under development for the Orion CEV. A preliminary design review for the CEV Ultraflex solar array development program is slated for January 2009, with the CDR scheduled for late 2009. This development program will fabricate and test two 6 m diameter qualification wings after the CDR. The development will be completed well before the need date for the Titan mission. For the TSSM SEP stage the CEV arrays would be modified to increase the output voltage from 28 V to a nominal value of 90 V at 1 AU. The higher voltage is required by the NEXT PPUs and also enables a substantial mass savings per solar array wing. A specific power of 175 W/kg (CBE) is assumed for the ultraflex solar arrays for the SEP stage, which is expected to be achievable by the end of this year.

The non-EP electronics on the SEP stage includes four assemblies, the SEP interface unit (SIU), the HVPA, the diode protection assembly, and the lightning suppression assembly (LSA). The SIU houses the solar array and ion thruster gimbal drive electronics as well as providing a 1553 interface with the orbiter. It reads all of the temperature sensors on the SEP stage and the two pressure transducers in the propellant management assembly (PMA), and houses the valve drivers for the PMA's two latch valves. Finally, it passes through 28 V power to the PMA pressure transducers.

The HVPA is a simplified version of Dawn's high voltage electronics assembly (HVEA), where the 28 V output high voltage-down-converters (HVDCs) have been omitted. The diode protection assemblies are also moved out of the HVEA and placed near the solar array wings. The LSA is included to provide a safe T-zero interface to the spacecraft on the launch pad.

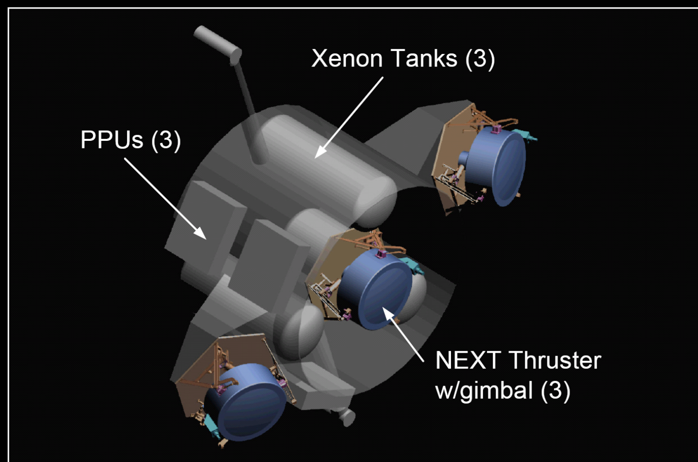
4.4.4.3 Block Diagrams

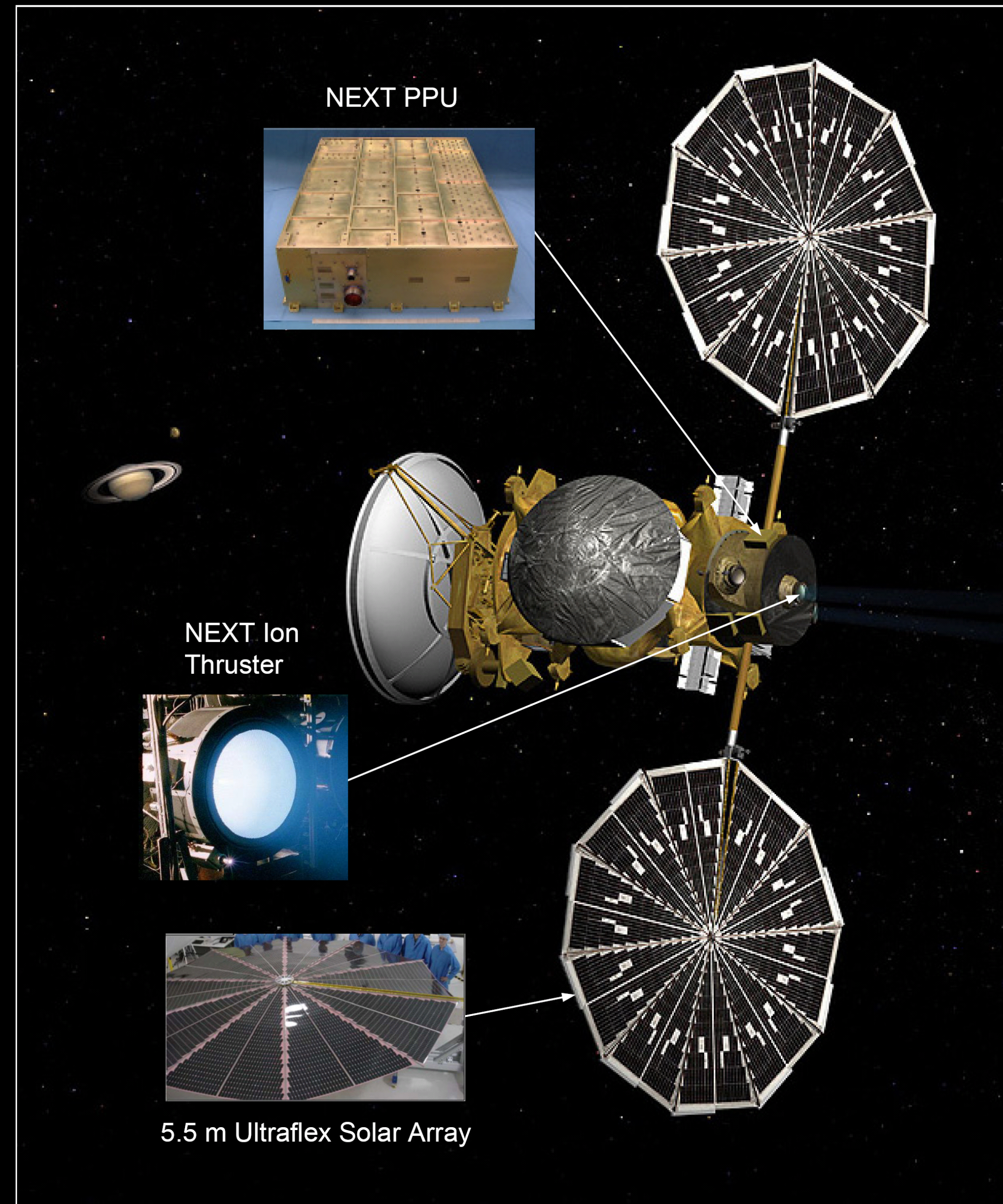
A simple block diagram of the SEP stage is given in **FO-3**. This diagram shows the three ion thruster / PPU / xenon flow control (XFC) / gimbal strings. Each PPU has a 1553 interface with the orbiter. The orbiter provides high-level commands to the PPU to start thrusting, set throttle level, and to stop thrusting. The PPU controls the operation of the propellant feed system and thruster in response to these commands. The orbiter's ACS provides commands to operate the ion thruster gimbals through the 1553 interface to the SIU.

The xenon feed system block diagram in **FO-3** includes three composite tanks of a custom size. These tanks are assumed to have

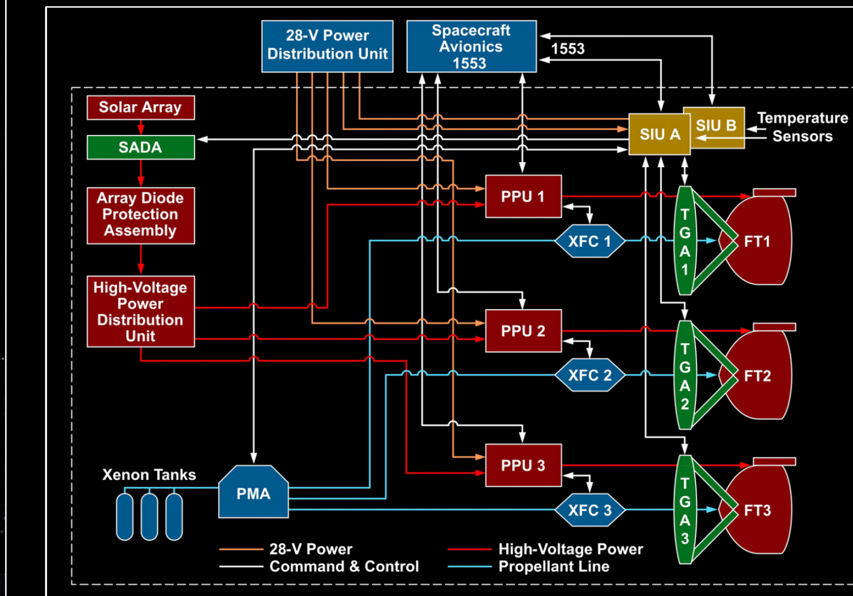
SEP Stage Characteristics

Total Dry Mass (w/contingency)	778 kg
Power (BOL @ 1 AU)	15 kW
Xenon Storage Capability	550 kg
Total Impulse	3 x 10^7 N-s
# Ion Thrusters	3 each
# PPUs	3 each

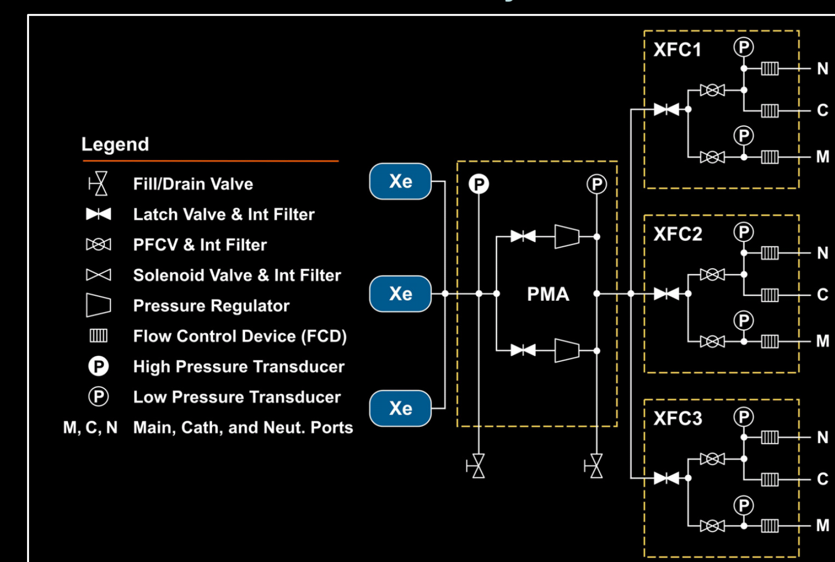




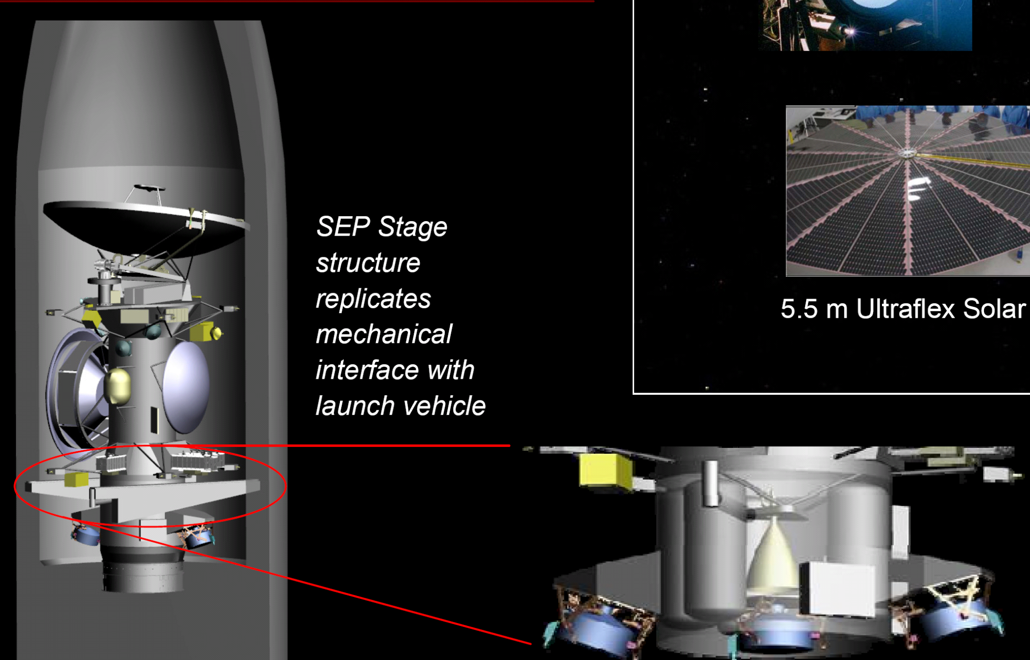
SEP Stage Block Diagram



Xenon Feed System



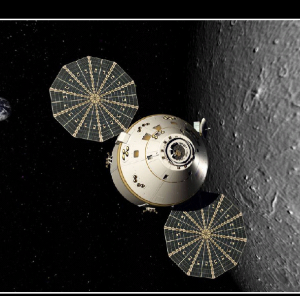
SEP Stage Configuration



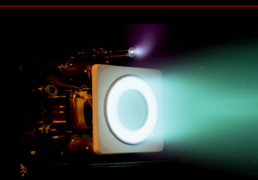
SEP Option Stowed in Atlas V Fairing

Integrated Stage Fits Around Orbiter Engine

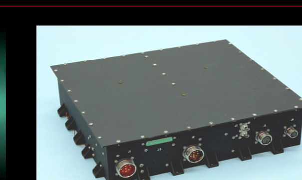
Two 7.5 kW Ultraflex arrays leverage development underway for Orion CEV



The BPT-4000 Hall Thruster could be adapted as an off-the-shelf alternative electric propulsion system



BPT-4000 Thruster



BPT-4000 PPU

Conceptual design

Figure 4.4-21. *Moog Propellant Management Assembly (PMA)*

the same tankage fraction as the Dawn xenon tank. Their design and fabrication is based on existing technologies for COPVs and will use seamless aluminum liners, while incorporating the lessons learned from the Dawn tank development. Each tank can store 220 kg of xenon and has a CBE mass of 9.2 kg. The high-pressure PMA shown in **Figure 4.4-21** is commercially available from Moog and is used by SS/Loral on their commercial communications satellites that employ Hall thrusters for stationkeeping. The XFC assemblies are a simplified, lower-cost derivative of the NEXT feed system and can operate the NEXT thruster over its full throttle range.

A block diagram of the orbiter and SEP stage power systems is given in **Figure 4.4-13** (§4.4.3.3). All of the power to run the SEP stage comes from the solar arrays with the following exceptions. The orbiter provides 28 V housekeeping power to each PPU and may provide some 28 V heater power if necessary. Most of the SEP stage heater power is provided by the solar arrays. The SEP stage has been designed to minimize the electrical interface with the orbiter. This interface includes only the Mil Std 1553 data bus to the PPUs and SIUs; 28 V power to the PPUs and SIUs; and the T-Zero umbilical.

4.4.4.4 Implementation Approach

The SEP stage will be implemented through close cooperation between JPL and GRC. GRC will be responsible for the delivery of the flight NEXT ion thrusters. This includes design, fabrication and testing of a qualification model thruster, as well as fabrication and acceptance testing of three flight model thrusters and one flight spare. GRC will also be responsible for the execution of an extended wear test of the qualification model thruster.

JPL will be responsible for the delivery of the SEP stage to assembly, test, and launch operations (ATLO). This includes procurement of the other ion propulsion system (IPS) elements, as well as the stage structure and power system. Make/buy reviews will be held in Phase B for each major component to determine the best implementation approach for TSSM. Integration and test of the SEP stage will take place at JPL.

4.4.4.5 ATLO Insertion

The SEP stage will be developed in parallel with the TSSM orbiter and is designed to minimize its impact on the orbiter. Development, integration and testing of the SEP stage are independent of the orbiter and off the critical path. After completion of the stage assembly and test, it will be mated with the orbiter for system-level testing. No hot-fire test of the thrusters on the spacecraft is planned. The experience with the Dawn ion propulsion system indicated that such a test should not be required on future spacecraft. What is required, and what is planned, is the operation of the PPUs in the SEP stage into resistive load over the full system input power range. This includes multiple PPU operation in all possible combinations and will be performed with the SEP stage mated to the orbiter while in system thermal-vacuum testing. In addition, each thruster will be operated in diode-mode with the ion propulsion system fully in the flight configuration. Xenon loading will be performed at KSC using the same loading approach successfully used on Dawn to load 415 kg of xenon in less than 25 hours.

4.4.4.6 Feed-Forward Benefits

Implementation of a SEP stage on the Titan mission using the NEXT ion propulsion technology will have significant benefits to a wide range of other NASA science missions.

NEXT Ion Propulsion System

For PI-led mission classes (Discovery, Mars Scout, and New Frontiers) cost risk and schedule risks are major concerns, and these missions require that new technologies be at TRL

6 at the confirmation review. Under the current TSSM SEP stage plan, NEXT risk reduction activities and subsystem qualification will occur early in the development program. The completion of qualification may align well with the anticipated confirmation reviews for future New Frontiers and Discovery mission cycles. The outcome of the TSSM NEXT development activities should exceed those requirements, further facilitating low-risk selection of NEXT for those mission classes.

SEP Stage

The TSSM SEP stage is a versatile high-energy upper stage capable of providing a total impulse of up to 3.2×10^7 N-s (approximately three times greater than that of the Dawn ion propulsion system). For the TSSM Flight System wet mass of 6203 kg the SEP stage uses only about half this capability to provide a ΔV of 2.75 km/s as required by the TSSM trajectory. For smaller spacecraft masses more characteristic of New Frontiers and Discovery missions, the SEP stage is capable of providing considerably higher ΔVs. For example, for a spacecraft wet mass of 1500 kg, the SEP stage could provide a maximum ΔV of 9 km/s and up to 12.4 km/s for an 800 kg spacecraft. This capability would encompass most or all of the near-term SEP missions that are currently being considered.

4.4.4.7 Backup SEP Option

As a risk-reduction backup option, mission designs (see §5.2) and a Mass Equipment List were developed for a SEP stage based on the use of the BPT-4000 Hall thruster. The overall mission performance is slightly degraded relative to the use of the NEXT thruster, but the BPT-4000 system is flight-qualified and commercially available, and can be used almost entirely without modification—slight changes to the gimbal would likely be required. The Hall thrusters are physically smaller than the NEXT thrusters, and four thrusters can easily fit within the SEP stage's cylindrical structure. These thrusters, however, operate at a lower specific impulse, resulting in a significantly higher propellant load. This larger propellant load can be accommodated on the SEP stage by mounting additional propellant tanks on the outside of the core cylindrical structure.

The acceptable performance and low cost and low risk of the BPT-4000 system makes this an attractive backup option.

4.4.5 *In Situ* Element Accommodation

The TSSM Flight System design includes accommodation for two ESA-provided *in situ* elements. These elements would be carried on the orbiter at launch and released at Titan flybys after SOI. Science data from the *in situ* elements would be relayed to Earth through the orbiter's telecommunications subsystem. This section provides an overview of the orbiter's resources dedicated to the *in situ* elements, the design features that enable their delivery to Titan, and the concept of operations by which their science goals would be achieved.

Mechanical Accommodations

The Flight System design for the Baseline mission provides accommodation for two *in situ* elements: an MMRTG-powered montgolfière and a battery powered lander. The lander, in a 1.8 m diameter aeroshell, has a mass of 190 kg. The montgolfière, in a 2.6 m diameter aeroshell has a mass of 600 kg. The ACS and Propulsion systems are designed to operate effectively with the *in situ* elements both attached and separated. **Figure 4.4-22** shows the smaller *in situ* element accommodation. The aeroshells interface with ESA-provided spin/eject devices, which are supported by an orbiter-provided probe support structure.

Power System Options

According to the agreement reached at the April 9, 2008 interim review at NASA Headquarters, NASA will provide ^{238}Pu power and heat sources for the ESA-provided elements. This will allow ESA to have a long-lived montgolfière mission returning enhanced science (see Appendix J). The cost of any RPS, as well as that of any RHUs used in the montgolfière and the lake lander, is included in the NASA mission cost. The heat generated by the RPS during cruise will be managed by the *in situ* element and not by the orbiter.

The MMRTG provided for the ESA montgolfière will be controlled, handled, and installed by NASA and its contractors. This will necessitate a close collaboration between NASA and ESA to ensure smooth processing in the critical weeks of launch preparations.

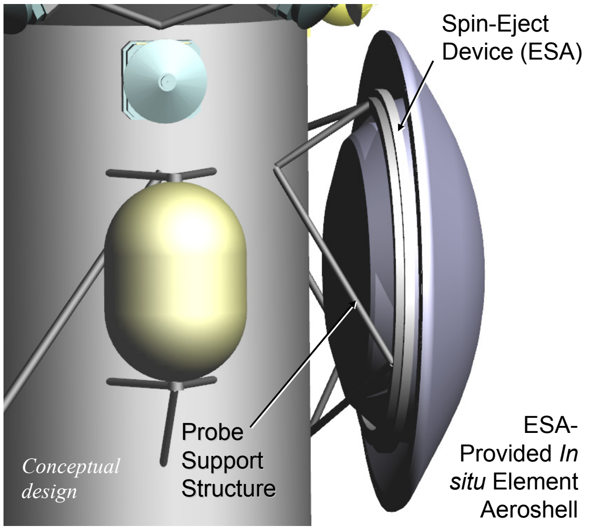


Figure 4.4-22. *In situ element accommodation.*

Full-scale models would be provided to ESA for fit-checks and environmental testing. However, current planning is for the actual MMRTG and the montgolfière to come together only at KSC in preparation for launch. The MMRTG will be mated to the montgolfière, as with the orbiter, for a fit-check and functional checkout at the payload hazardous servicing facility PHSF prior to final installation. The final installation will occur at the payload processing facility prior to encapsulation and transportation to the pad.

The battery-powered lander will be provided with main bus power both for testing and for the duration of the Interplanetary Cruise Phase of the mission. It is expected that the lander will be powered by a primary battery, not a rechargeable battery; this requires a power interface for cruise phase operations, such as health checks.

Communications

When the *in situ* elements are mounted to the orbiter, communication between them and the orbiter will be through RS-422 connections. These will be treated as any other instrument interface to the C&DH subsystem (see §4.4.3.5 for details and block diagram). This will facilitate ground testing and launch operations, as well as cruise phase operations.

After separation from the orbiter, the *in situ* elements will communicate with the orbiter through the orbiter's RF communication subsystem; no additional orbiter hardware is required. The UST used in the orbiter telecom subsystem has the flexibility to communicate in multiple channels in X-band, allowing a dedicated channel(s) for *in situ* communications without additional hardware.

The orbiter will release the montgolfière on the first Titan flyby after SOI. The orbiter will track and observe the montgolfière's Entry, Descent, and Inflation (EDI). The orbiter will store all data transmitted by the montgolfière and forward this data to the Earth. The orbiter will continue to track the montgolfière whenever it is in view during the Saturn Tour Phase, collecting and forwarding its data to the DSN.

The orbiter will release the lander just prior to the second Titan flyby. The orbiter will track and observe the lander's Entry, Descent and Landing (EDL). The orbiter will, again, collect and forward the lander's data to the Earth for the duration of its nine hour mission. There will be no periodic communications with the lander after this event, because lander life is short.

During the primary mission of the *in situ* elements, their data will be downlinked from the orbiter at the highest priority. The only exception may be for the orbiter's own data taken from encounters with Enceladus. This communication scheme will continue during the Saturn Tour, interrupted only by critical orbiter events.

4.4.6 Verification and Validation

TSSM will verify and validate the mission system to ensure it meets specifications and is capable of accomplishing the science objectives. A combination of system analysis, modeling and simulation tools, engineering development unit hardware and testbeds, flight software testbeds utilizing simulations and EM hardware, Flight System functional/environmental testing, ATLO and readiness tests will be used.

Simulation Capability

A high fidelity model-based simulation capability (S-Sim) is baselined for flight software test and verification. In addition to flight software verification the S-sim environment is capable of supporting fault protection, ACS, system level V&V, and mission activity development. The first S-Sim version will be available to support the first flight software release and continue with expanded capability in

support of testing of subsequent flight software builds. The simulation environment will be available on all software developers' and testers' workstations (full software simulators). These simulators will be built to allow for interchangeability between software models and hardware EMs later in the "hardware-in-the-loop" testbeds in a manner that is transparent to the flight software. This allows the same test scripts to be used whenever the testbed models are interchanged with EMs. S-sim will provide full Flight System simulation in a closed loop environment, operating in nominal and off nominal modes.

In addition to the simulation capability described above, TSSM will have three primary system testbeds: two single-string and one dual-string. The Mission System Testbed (MSTB) is a dual-string high-fidelity testbed that is dedicated to system verification and validation (V&V), Flight Software fault tests, mission system tests, and ATLO support. The Flight Software Testbed (FSWTB) is a single-string "hardware-in-the-loop" testbed that is dedicated to Flight Software and Flight Hardware integration. The Flight Software Test Bed is also dedicated to Phase E software maintenance, development and trouble-shooting. Additionally, there is one GSE development station called the Realtime Development Environment (RDE) that is dedicated to Ground Support Equipment (GSE) hardware and software development and test, test script development and validation, and database maturation.

These testbeds will include the C&DH, ACS, power, telecom and harness subsystems. Only the MSTB will have hardware versions of the engineering subsystems; they will be simulated on the other testbeds. Multiple workstation testbeds will also be available to all software developers and testers during development. The testbeds will include the Ground Data System (GDS) hardware and software as well.

The EM versions of all Flight System engineering subsystems and instruments are included in the testbeds for integration and interface verification. Flight units are delivered directly to ATLO after thorough testing is completed by the delivering organization. No flight units are required to flow through the testbeds unless there are major modifications from the EM, however, the testbeds can support flight hardware integrations if needed. There will be a simulation environment for V&V that can off-load the hardware-in-the-loop testbeds as well as using the EM integration effort to help enhance evaluation of model fidelity. The simulation environment interfaces and procedures will be compatible with those of the hardware testbeds. The testbeds will also be used to train test analysts to support ATLO testing as well as to support ATLO procedure development and anomaly investigation. All flight software versions will be verified on the testbeds prior to being loaded onto the Flight System in ATLO or in operations. **Figure 4.4-23** depicts the test-bed utilization with major flight software release and ATLO schedule.

ATLO and I&T Approach

The TSSM system integration and test (I&T) approach is modeled after the Cassini-Huygens ATLO effort, as these two missions share a great deal of similarity in complexity and design, including the accommodation of a European-provided *in situ* element. TSSM differs from Cassini-Huygens in that one of its two *in situ* elements will be powered by an MMRTG. Additionally, the TSSM Flight System includes a SEP stage for its early cruise phase. The SEP stage will be developed, integrated, and tested in parallel with the orbiter and delivered to ATLO for system-level testing.

The JPL 25-foot thermal vacuum chamber will be utilized for system thermal vacuum testing of the orbiter with two planned tests, one with the SEP stage and one without the SEP stage. The JPL vibration and acoustic test cells will be utilized for all dynamics testing of the orbiter. A new overturning-moment-restraint system will be installed for the upgraded vibration table under JPL capital improvement programs. As was the case for Cassini, this is necessary to safely test the spacecraft for its large mass and high center-of-gravity. ESA will utilize its facilities for ATLO of the lander and the montgolfière; which arrive at KSC directly for integration. Mass and electrical simulators for these items will be utilized at JPL for all spacecraft-level verification.

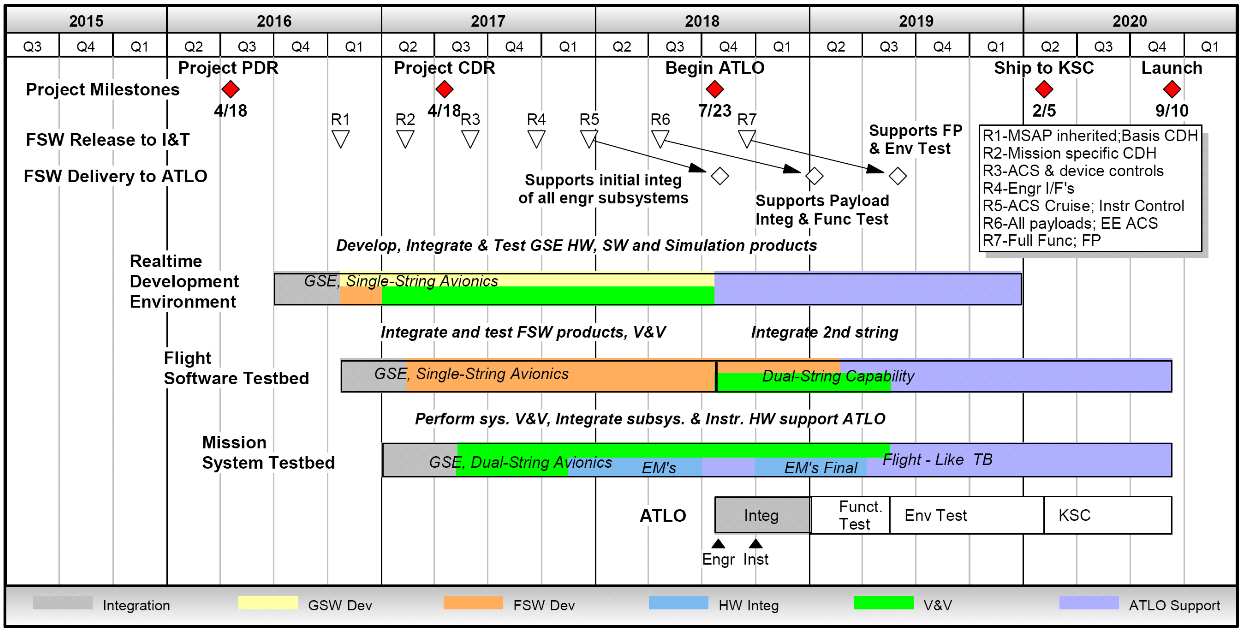


Figure 4.4-23. *Test-bed utilization with major flight software release and ATLO Baseline schedule.*

All testing will be performed by ATLO system engineers, with extensive support from subsystem and instrument engineers and the actual operations team. The TSSM GDS will be used in all the functional and performance tests to allow for end-to-end data flow testing and tool suite validation. Operational Readiness Tests (ORTs) will be performed to assess the infrastructure and team's ability to execute the operational phases of the mission.

A Developmental Test Model (DTM) will be built that will effectively be the EM for the Flight System structure. The DTM is used to alleviate the schedule impact on the flight unit. The DTM will be used to do static and modal testing which allows the flight unit to be integrated in parallel. In addition, the DTM is used to do fit checks and cable or mass mock ups. This model along with a DTM for the lander and montgolfière, provided by ESA, will also be used as a fit check "trailblazer" at the launch site to ensure that the procedures and processes for integration of the RPS to the Flight System are compatible and streamlined during the launch preparations.

A trailblazer activity is required to plan and execute the integration activities for installation of the RPSs in the montgolfière and orbiter, encapsulation, transport to the pad, lift and mate operations and final closeouts. Planning begins early in Phase B, where requirements and storyboards are put together to understand the constraints imposed at the launch site. Mockups of the hardware and facilities are created to physically simulate the integration. Ultimately, the GSE, RPS simulators and DTM meet at the Cape to walk thru the simulated installation process to ensure adequate clearances, procedures and safeguards.

The ATLO schedule and I&T plan are summarized in **Foldout 4** (**FO-4**). This process is designed to provide verification of the Flight System design and workmanship by subjecting the Flight System to a demanding series of functional, operational, and environmental tests, while also maintaining the integrity of the planetary protection approach. Initial assembly begins with delivery of the Flight System primary structure, the propulsion subsystem and the electrical cable harness. Each electrical subsystem undergoes vibration, thermal, pyroshock, Electromagnetic Compatibility/Interference (EMC/EMI) and magnetics testing/characterization, and potentially, sterilization processing prior to delivery to ATLO. Each subsystem with electrical functionality is integrated using assembly plans and test procedures that ensure mechanical and electrical safety and which have been verified

in the testbed. Once all of the engineering subsystems are safely integrated and fully functional at the system level, the instrument payloads are integrated with the spacecraft to complete the Flight System. Simulators and EMs are used for the *in situ* elements. A preliminary Incompressible Test List is generated by Project CDR and approved by the System Integration Review (SIR) to identify and assure that all critical testing is performed on the Flight System prior to launch. To ensure that a complete and comprehensive system-level test program is provided, ATLO V&V is augmented with payload simulators, engineering models and the DTM.

The TSSM team will maintain a rigorous formal program for testing flight hardware at all levels of assembly ("test as you fly and fly as you test" philosophy). Electrical testing includes component interface tests, Flight System functional tests, DSN compatibility tests, instrument interface verifications, performance tests and environmental tests. All electrical test procedures are verified on the testbed prior to being run on the Flight System. Similarly, all flight software versions are run through the testbeds before being uploaded onto the Flight System in ATLO.

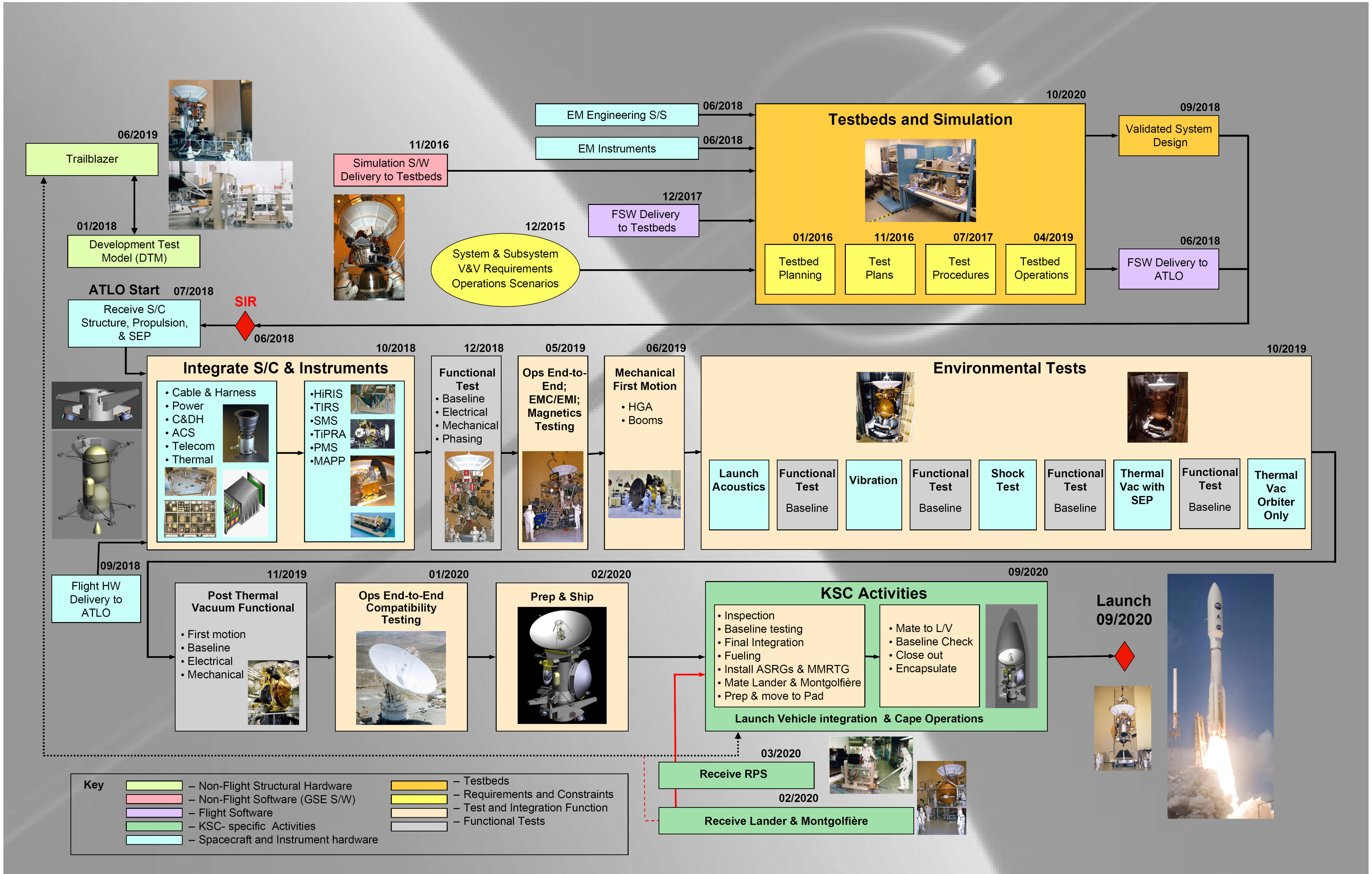
The TSSM environmental test program consists of a comprehensive system level test program that ensures that the Flight System has been verified to operate in the expected environments of the mission. At the subsystem or assembly level, all flight hardware will be tested to acceptance levels and durations if there has been a preceding qualification test or to protoflight levels and durations if no qualification unit was available. System level environmental tests include system level acoustics, vibration and shock, thermal balance, and thermal vacuum. The system level EMC/EMI, and magnetic cleanliness verification is performed via modeling of the assembly and subsystem level testing performed prior to ATLO. Modal surveys are also performed to validate the Flight System structural model. Functional tests are repeated after each environmental test to ensure that the test effects have not degraded system performance. Post-environmental tests also facilitate verification of any modification to flight software or flight sequences (see **FO-4**).

All flight engineering subsystems are required to track powered-on time. Flight engineering subsystems (including backups) other than instruments are required to accumulate 200 hours prior to integration and 500 hours (with a goal of 1000 hours) at the system level prior to launch. Instrument electronics are required to accumulate 300 hours prior to integration and 200 hours at the system level prior to launch.

The Flight System is enclosed and trucked intact under air conditioning to the launch site. Functional testing is performed prior to and immediately after shipment to verify that the shipment did not adversely affect its performance. The flight lander and montgolfière are delivered directly to the launch site by ESA. Post-ship validation and RPS integration will occur in dedicated facilities to ensure adequate cleanliness for planetary protection. Once their aeroshells are installed, the lander and montgolfière can be processed within the same cleanliness environment as the orbiter. Complete integrated interface, functionality, and performance testing with the orbiter will be performed at this time.

The RPSs will be delivered separately to the launch site by the DOE. Evaluation of the RPS integration at the Cape has been revisited since the 2007 study and confirms that the montgolfière design does not lend itself to launch pad integration of the MMRTG. For TSSM, the RPS integration both for the montgolfière and the five ASRGs on the orbiter would occur at the Payload Hazardous Servicing Facility (PHSF) prior to start of launch vehicle fairing encapsulation operations. There is historical precedence for integration of RPS units with flight systems in the PHSF. On New Horizons, the GPHS RTG was brought to the PHSF where the full suite of mechanical and electrical integration procedures was performed. At the completion of electrical checkout, a de-installation procedure was used to remove the RTG. Ultimately, the final RTG installation for flight was performed on the launch pad. As with any mission that uses RPSs, program-specific integration and handling procedures will be required. The effort for generating these procedures for TSSM is included in the trailblazer activities.

FOLDOUT 4
ORBITER VERIFICATION AND VALIDATION



The 2007 Titan Explorer study engaged personnel from KSC to assess the feasibility of final flight installation of RPSs in the PHSF. The results of this assessment led the Titan Explorer team to baseline this approach and the TSSM team has chosen to follow the same path.

Following RPS integration the integrated stack, encapsulated within the fairing and air conditioned as necessary, would be transported to the pad for launch vehicle mate. Thermal and contamination control would continue up to the time of launch. There is precedent for this sequence with the Voyager missions. The significance of the DTM is greatly increased in order to ensure that all handling operations are demonstrated and rehearsed to ensure spacecraft and personnel safety.

4.4.7 Completed Trade Studies

High-level mission architecture trades for TSSM are documented in §3.0. The TSSM team also conducted several technical design trades, which were documented separately. **Table 4.4-12** shows a summary of these completed trades. The two most significant trades resulted in the inclusion of a SEP stage and the incorporation of ASRGs into the TSSM design. Details on the SEP stage design can be found in §4.4.4. Details on the ASRG implementation can be found in §4.4.2.2.

Throughout this year's study, several configuration trades were completed to balance science needs, instrument placement, risk, and operational scenarios. The current configuration is a result of these trades and includes two different spacecraft flight orientations: one for the Aerobraking Phase and one for the Circular Orbit Phase. The configuration trades are too numerous to detail in this report; optimization of the configuration will continue through Phase A.

Table 4.4-12. *TSSM completed trade studies.*

Trade Name	Trade Options	Discussion
SEP	**Include SEP Stage** vs. Chemical Only Propulsion?	Although approximately $100M more expensive, the inclusion of a SEP stage significantly reduces trip time and enhances mission flexibility.
SEP Architecture	Integral vs. **Separable SEP Stage**	A separable SEP stage was chosen for the TSSM design as it allows for a significant mass jettison before SOI, thus increasing delivered mass capability to Titan. Design of the SEP stage as a self-contained unit also results in a feed-forward flight element that would be available to future missions.
RPS System	MMRTG vs. **ASRG**	ASRGs were chosen based on their reduced mass, increased power output, and reduced cost. If a programmatic decision is made to use MMRTGs, TSSM is carrying extra mass margin (above the required 33%) and power margin to accommodate either RPS system.
Power Requirements	4 vs. **5** vs. 6 MMRTGs	Power requirements for science instruments and telecom dictated the use of the equivalent of 5 MMRTGs. With 4 MMRTGs, inadequate power would be available to operate instruments (the duty cycles would have to be unacceptably low). 6 MMRTGs would make a more comfortable science scenario, but would cause the mission to exceed the study guidelines for available plutonium quantity when combined with the MMRTG on the montgolfière and RHU demands. Unless NASA directs the use of MMRTGs, this trade is no longer applicable due to a change in study guidelines allowing the use of ASRGs. Subsequent analysis showed 4 ASRGs accommodates the power requirements met by 5 MMRTGs, (and even provides more power than the 5 MMRTG case). A 5th ASRG is carried as an onboard spare for redundancy.
OpNav Camera	**Include OpNav** vs. No OpNav	Optical navigation is needed to determine the orbit of Enceladus to sufficient accuracy to enable low-altitude flybys. Without optical navigation, the altitude of these flybys would likely be limited to 500 km; with OpNav these flybys could go as low as 25 km (as demonstrated in Cassini's Equinox Mission).
Fine Attitude Control	**RWAs** vs. MIT Thrusters	RWAs were chosen to perform 3-axis control because, while the MITs require less power (by ~35 W) and will potentially cost less, they may require a large mass hit in hydrazine propellant. The RWAs will provide slightly better pointing control, especially with respect to pointing stability. The MITs have uncertain development and qualification costs at this time.

Trade Name	Trade Options	Discussion
IMU	MIMU vs. **SIRU**	Although the MIMU is less massive and costly (even though 2 are required for redundancy), there are concerns with the MIMU's lifetime. The internally-redundant SIRU was selected for its longer life capability. This trade will be revisited in Phase A.
Thruster Layout	**Coupled** vs. Uncoupled Thrusters	Coupled thrusters were used in the TSSM design to avoid accumulation of unwanted ΔV errors. Additionally, during the release of the *in situ* elements, coupled thrusters provide double the control authority, and therefore higher reliability.
Main Engine	**Single** vs. Dual	Outcome of a propulsion subsystem review. Two engines for redundancy introduces complexities that have not yet been worked. The expenditure of resources (cost, mass) to implement this redundancy was not deemed the best use of these resources to justify a two main engine implementation at this time. Will revisit in Phase A.
Thrust Control	**Gimbaled main engine** vs. TVC thrusters	Outcome of a propulsion system table top review. Though a gimbaled main engine is more costly, it is a more robust design. Gimbaling provides a wider range for the center of gravity, which is especially important with the release of two large *in situ* elements.
Engine Cover	**Include Engine Cover** vs. No Engine Cover	Concern of particulates damaging the engine during Saturn ring crossings, Enceladus plume flybys, and engine-first Titan aerobraking segments of the mission, as well as the long lifetime requirement on the engine.
Propellant Tank Material	Titanium vs. **COPV**	COPV tanks are industry standard and are significantly less massive and less expensive than traditional Titanium tanks.
Propellant Tank Configuration	**Tank Mass** vs. Spacecraft Stack Height	Although a trade was conducted to determine system-level mass savings for increasing tank width (and therefore mass), but reducing spacecraft stack height (and therefore decreasing overall system mass), ultimately the stack height was not reduced due to *in situ* accommodation needs.
HGA Pointing	Monopulse tracking vs. **Spacecraft pointing w/ stiff antenna**	TSSM has an MRO-derived antenna design for maximum stiffness. This includes a body-fixed gimbal platform for the antenna. The open-loop spacecraft pointing design using the stiff antenna was considered the more robust, lower cost option when compared to closed-loop monopulse tracking. Additionally, spacecraft pointing requires a lower demand on DSN resources.
HGA Diameter and Articulation	3 m vs. **4 m, gimbaled** vs. body-fixed	The 2007 Titan Explorer study made use of a 3 m HGA, but this earlier study assumed 70 m receiving stations. Because of the 2008 guideline not to assume 70 m stations, it was decided to adopt the larger antenna to recapture some of the data rate that would be lost by relying on the 34 m ground stations. To fit within the confines of the LV fairing, the antenna was positioned on the top deck of the orbiter. This axial location has the added benefits of protecting the spacecraft during ring crossings, serving as a sun shade, and acting as an aerodynamic stabilizer during aerobraking. Deciding to articulate the HGA (instead of putting the instruments on a scan platform or body-fixing the antenna and instruments like Cassini) came out of the operations lessons learned activity documented in Appendix K.
Radio Science and Relay Communication	**UST** vs. SDST	The UST accomplishes orbiter-to-Earth communication, relay communication with the *in situ* elements, and Ka-uplink (a science requirement) in a single unit, thus taking the place of a SDST, an Electra, and a Ka translator. While the SDST is flight proven, it is currently out of production. The UST is under development, and will be monitored carefully throughout Phase A.
Safe Mode Communication	USO vs. **USO not required for communication**	USO is not required for Flight System safe mode operations (an initial concern), but was included in the design for science purposes because it enables radio occultations in Titan's atmosphere.
C&DH System Interfaces	**MSIA Card** vs. MREU	MSIA is the card used in the MSAP C&DH architecture to interface with other spacecraft systems (in TSSM's case, the *in situ* elements and the OpNav camera), but the MSIA uses significant power. An alternative architecture using a MREU in place of the MSIA was investigated, but did not realize the power savings originally hoped for and complicated the design.
Memory Type	Flash vs. **SDRAM** vs. SRAM	Flash memory is very sensitive to radiation (tolerant to only 7 krad), and would therefore require significant shielding to meet even the modest radiation requirements of this mission. SDRAM was chosen for its rad hard availability and because it provides more memory when compared to a SRAM card with the same sized footprint.
Instrument Interface Type	SpaceWire vs. **Diversified Interfaces**	The goal of the TSSM C&DH design was to maximize the use of current MSAP designs. To use a SpaceWire-only system (a high-speed, low error rate interface) would have resulted in modifications to the current MSAP SFC card, which has only four SpaceWire ports. The current TSSM design utilizes SpaceWire and RSB for instrument interfaces and 1553 to interface with other spacecraft subsystems.

4.5 Ground System

Experience and lessons learned from previous mission such as Cassini-Huygens has shown that early and comprehensive consideration of the ground system is vital to mission success. For this reason, the TSSM project will develop the ground system at the same time as the flight and science systems, which are also described in this report.

4.5.1 Ground System Architecture

The description of the ground system architecture in this report is intended to provide detailed information for the ground system elements, mission operations system, and the Deep Space Network (DSN) scheduling rationale.

The ground system elements are the multi-mission system, which includes the DSN and several data processing and transport systems; the mission operations system (MOS) which is the people, procedures, and the facilities to operate the mission, and includes the physical and software infrastructure to perform the mission operations as the ground data system (GDS); and the science planning, analysis, and archive functions for the project. These descriptions are consistent for JPL missions of the scope of TSSM, they are used for cost estimation purposes, and have been modified as necessary for the unique features of TSSM.

The DSN scheduling rationale is described for all phases of the mission and is used for mission cost analysis and data return scenarios.

The ground system is illustrated in **Figure 4.5-1**, and is made up of the three major elements necessary to successfully operate the mission. This figure shows the NASA wide common services and capabilities provided by the multi-mission systems; the project specific MOS with its underlying ground data system; and the science support elements.

The TSSM ground system used a generic or typical ground system implementation as a minimum cost starting point. Modification and expansions of the generic ground system, as required to meet the specific requirements and needs of the TSSM mission are discussed further in this section. This ground system architecture and implementation will continue to evolve during the course of the development and operations of the TSSM mission.

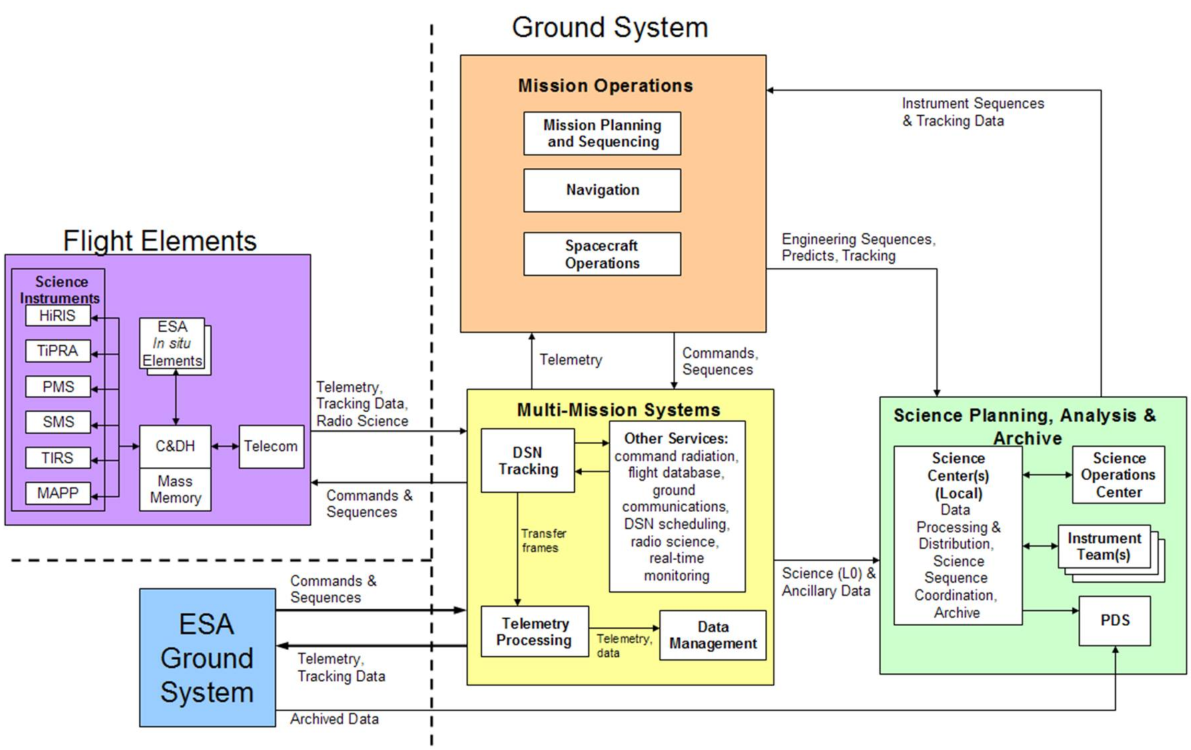


*Figure 4.5-1. Ground system data flow diagram (see **Figure 2.4-24** for SOC details).*

4.5.1.1 Multi-Mission Systems

The multi-mission systems handle the communication interface between the Flight System and the rest of the ground system. The multi-mission system includes the Deep Space Network (DSN), the underlying interconnecting ground network, and the related services. The services support initial processing of the telemetry and the related data management and distribution of the telemetry data to specific interfaces, such as the science processing organization and spacecraft analysis teams.

The DSN, which currently consists of three complexes (Goldstone, USA; Canberra, Australia; Madrid, Spain), will perform all tracking for this mission, except for launch tracking support. For launch support up through final injection burn, the mission tracking will use the 9 m to 12 m X-band ground stations of the NASA Ground Network at Cape Canaveral, Florida and elsewhere around the world along the flight path. The actual stations used depend significantly on the ascent trajectory. Once the DSN takes over the tracking duties it will follow a profile along the lines as described in **Table 4.5-1**. Only the 34 m stations (there are several at each complex) are to be used for science data downlink for this mission. During Titan circular orbits, the DSN will track the orbiter spacecraft for 14 passes per week, or two 8 hour passes per day. Since Titan must be at least 20° above the local horizon at the DSN complex in order to receive data at the planned data rate (Ka-band), there was a concern that Titan would not be visible long enough to receive all of the planned science data. However, an analysis has shown that while Titan will not be visible to the Canberra complex for a sufficient amount of time, there will be more than sufficient time for downlinking all of the planned data using antennas at the Madrid and Goldstone complexes.

As specified in the study Ground Rules, these operations scenarios assume that only 34 m antenna complexes will be used for communication between the Flight System and the Earth. The use of the DSN 70 m (or equivalent) antennas will only be used for coverage of critical events (such as EDI/EDL) and for communications in case the spacecraft enters safe mode. As opportunities become available to increase mission performance using enhanced DSN capabilities, these opportunities will be studied for possible inclusion in the mission plans.

In addition to the DSN, multi-mission systems also provide other services. These services include telemetry processing and distribution, commanding, real-time monitoring and control, scheduling, radio science, and ground communications infrastructure. The telemetry services will take the data stream as received at the DSN stations and convert it to level 0 data products (as the data appeared on the Flight System prior to transmission). The telemetry system also performs additional processing to separate the instruments data from the spacecraft data, stores the data in the project database for non-real-time analysis, and distributes telemetry data to the appropriate customers. The command service takes the command files generated by the MOS and radiates them to the Flight System. The real-time monitoring and control team, also known as the mission control team, act as the interface between the mission and the DSN operations, and provide ongoing monitoring of the telemetry being received and of the command radiation activities, ensuring timely responses to problems in communications. Scheduling services ensure the project is able to get the DSN tracking resources needed routinely and for emergencies and are key to resolving conflicts with other missions over the limited resources of the DSN. The radio science service provides data to the radio science team.

A critical, but often overlooked service is the ground communications network support. This final service provides as a minimum the communications between JPL and each of the DSN complexes and voice nets used by the project. More frequently, this service is also extended to implement and support remote science or spacecraft operation centers. A key part of this support is the team of network system administrators that ensure the continued functioning of the network, network security, and voice communications.

Table 4.5-1. *Planned DSN schedule by mission phase.*

DSN Coverage					
Description	**Subnet**	**Year**	**Hours/ track**	**Tracks/ week**	**Duration (weeks)**
Interplanetary Cruise Phase September 2020 to October 2029					
Launch and Early Operations: Begins with the launch countdown. Activities include initial acquisition by the DSN, checkout and deployment of all critical Flight System systems and a major maneuver to clean-up trajectory errors from launch vehicle injection				September/October 2020 30 day duration	
Launch to L+30	34 BWG	2020	8	21	4
Cruise: Activities include science instrument calibrations, Venus and Earth gravity assist flyby science operations, SEP thrusting and coasting, and operations readiness testing. Ends with SEP release.				October 2020 to October 2025	
EVEE GA	34 BWG	2020–2025	8	15	12
EH&S + Nav (during SEP thrusting)	34 BWG	2020–2025	8	1	94
ΔDOR	34 BWG	2020–2025	1	0.5	94
EH&S + Nav (Coast) + Inst health checks	34 BWG	2020–2025	8	3	25
EH&S + Nav (Coast)	34 BWG	2020–2025	8	0.5	130
Saturn Approach: Activities include final preparations, training, and ORTs for all mission elements in preparation for SOI and Saturn moon flybys.				October 2025 to SOI (October 2029)	
EH&S + Nav (till SOI – 2m)**	34 BWG	2025–2029	8	3	190
SOI Approach Heavy tracking**	34 BWG	2029	8	21	3
SOI Approach Light tracking**	34 BWG	2029	8	14	3
SOI	34 BWG	2029	8	21	2
Saturn System Tour Phase October 2029 to July 2033					
The phase is characterized by continuous science observations of the Saturn system and multiple (20+) flybys of major Saturn satellites. The final month of the phase is dedicated to targeting maneuvers in preparation for TOI.				SOI to TOI (October 2029 – September 2031)	
Saturn System Science	34 BWG	2029–2031	8	7	34
Flyby: Prep & Science (x21)	34 BWG	2029–2031	8	14	42
Relay support + Saturn Science	34 BWG	2029–2030	8	14	24
Titan Aerobraking Phase September 2031 to November 2031					
Begins with Titan Orbit Insertion and continues for 2 months of aerobraking.				September 2031 – November 2031 (60 days)	
TOI	34 BWG	2031	8	21	1
Aerobraking coverage	34 BWG	2031	8	21	8
Titan Circular Orbit Phase November 2031 to July 2033					
Begins after the initial aerobraking has ended and continues for 20 months. This phase is characterized with different science campaigns.				November 2031 – July 2033	
Mapping	34 BWG	2031–2033	8	14	95
Ka-band Radio Science	34 BWG		8	7	95

**ΔDOR tracking would be used during approach and as needed during cruise, not called out separately.

For TSSM, the multi-mission systems will enhance the information security capabilities, processes, and procedures from the Cassini mission to fit the current higher security requirements. From an information security standpoint, the Cassini mission was very similar to TSSM, since this was also a nuclear powered mission that executed an Earth flyby, and TSSM can build on this system. However, the current higher state of security requirements means that for this Titan Saturn mission, the Cassini level of security may need to be enhanced. This will be especially true in the area of ensuring command integrity for all commands and sequence sent to the spacecraft.

4.5.1.2 Mission Operation System

The Mission Operation System (MOS) is made up of the project specific people, processes, software, and hardware used to operate

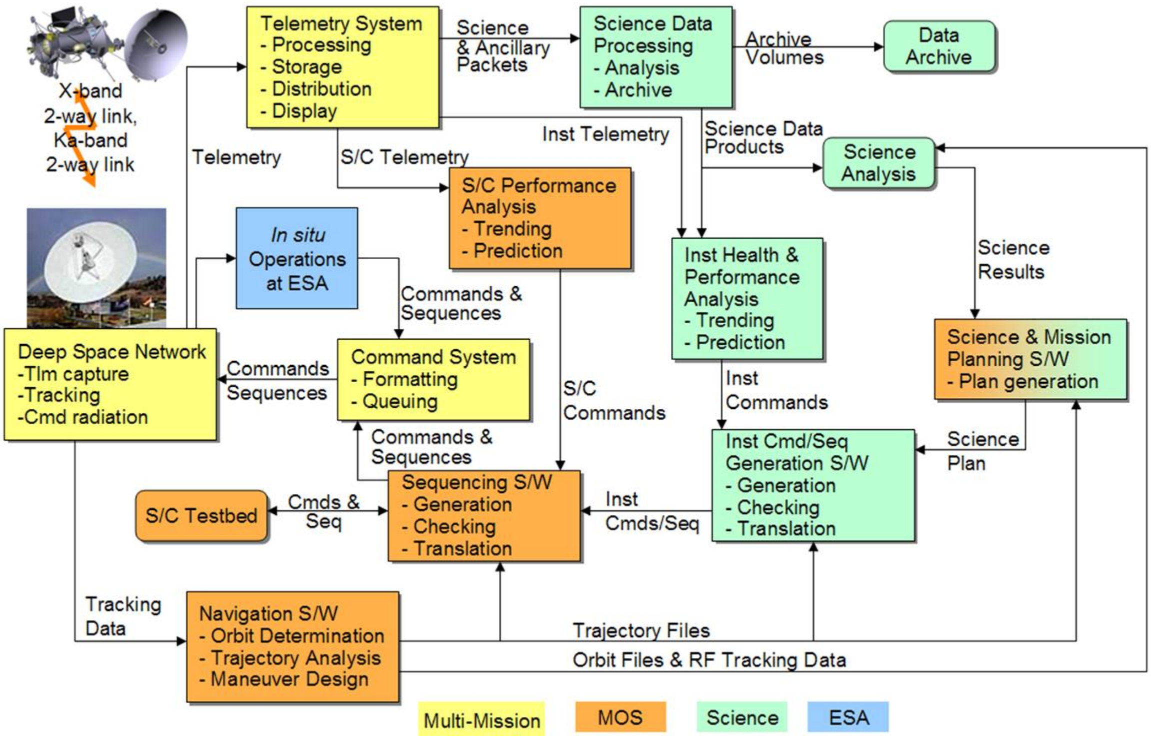


Figure 4.5-2. *Mission operations system function and product flow diagram.*

the spacecraft and instruments, and for processing, storing and archiving the data associated with operating the spacecraft and instruments. Key elements of the project specific elements of the MOS include: the infrastructure support, spacecraft operations and analysis, navigation support, mission planning and sequence development, and training. **Figure 4.5-2** shows the functional flow of products among the MOS elements in the project.

Underlying all of the functions and communication paths is the support infrastructure. This includes the system administrators, developers, and supporting hardware. Prior to launch the multi-mission Ground Data System (GDS) is adapted across all elements of the ground system to handle the mission specific functions and requirements. After the initial delivery, the underlying multi-mission GDS undergoes periodic revision; about every 6 months (more frequently during ATLO) during the development phase and after launch, about every 18 months for major bug fixes, operating system updates, and general maintenance. These periodic updates and project specific changes to the GDS, which can occur more frequently, will be tested as needed. Ground System planning has also allocated staffing to support major deliveries (primarily of planning and sequence related tools) around each interplanetary gravity assist, and about 12 months before both SOI and TOI. These post-launch updates are to incorporate lessons learned during the mission and newly available technologies. In addition, about every 3 to 4 years the GDS computers and related hardware will be replenished to ensure that the hardware and operating systems support will be available throughout the life of flight operations.

The TSSM project is planning on the development of advanced planning and operational tools to help reduce the cost and increase the effectiveness of the ground system. This assumption is based on the continuation of work currently under way. For example, JPL is performing internal work to improve and reduce the cost of operations through the Robust Operations Working Group (ROWG). This work is augmented by the Multi-mission Ground Support System (MGSS) Program Operating Plan (POP) cycle funding which is proposing similar work. Additionally, the Model Based Engineering task in JPL's Sys-

tems & Software Division is working to improve the spacecraft modeling and analysis tools. However, the TSSM project should also provide seed money in these areas to augment, provide focus, and demonstrate support and desire for the development of these advanced tools and operations technology.

Spacecraft operations teams monitor spacecraft health and develop sequences for the spacecraft. The spacecraft subsystem engineers use the spacecraft engineering telemetry to perform general spacecraft health analysis and trending. The spacecraft subsystem engineers also participate in fault diagnosis, anomaly resolution, and prediction of future behavior, and sequence development and review.

The navigation team performs trajectory analysis and design, and will also support Titan and Enceladus (Radio Science) gravity mapping. The navigation team performs the orbit determination and trajectory analysis for the Flight System using DSN RF data and, if needed, on-board imaging data. The navigation team also coordinates with instrument and spacecraft teams to implement planned propulsive maneuvers and reaction wheel desaturation burns, predict flyby geometry and timing parameters, and plan future mission phase trajectories.

Mission planning is an ongoing function for the life of the mission and involves the cross-project coordination, planning and analysis of the trajectory design, mission timelines, and the major activities during each of the mission phases. This is performed with membership across the project including support from spacecraft, navigation, instrument and science teams. Once the Flight System is operational, mission planning coordinates the refinement of trajectories and activities to compensate for changing plans and evolving Flight System characteristics, and to fine-tune specific events such as flybys, checkouts and instrument calibrations.

Training activities are required to maintain personnel skill levels and to prepare for mission operations. Activity planning, uplink product generation, flight and ground system software updates and testing, operations rehearsals and Operation Readiness Tests (ORT) support personnel training and readiness. These activities validate procedures and prepare the teams for upcoming critical events. During ATLO, missions typically conduct ORTs and other test and training activities for launch, the first major maneuver, and for any mission critical event that could cause a loss of mission if done incorrectly. For the long duration of TSSM mission skill retention issues will necessitate additional training. Team training activities will be planned at regular intervals and will include post launch training activities and ORTs for each of the gravity assist encounters, SOI, the Enceladus and Titan flybys, TOI and aerobraking, and the Titan orbit campaigns.

Sequences will be developed by many teams and will be centrally integrated and tested. The spacecraft team develops the sequences for the spacecraft based on the mission plan, inputs from navigation, and the results of subsystem analysis and trends. The science operations teams create sequences for each instrument based on mission plans and science observation plans, coordinating with campaign teams and the spacecraft team to ensure proper sharing of resources. The spacecraft and science sequences are integrated together and tested to ensure that they do not violate flight rules, endanger the Flight System, do not conflict with each other, and will function correctly.

The length of the TSSM science and engineering sequences will vary over the course of the mission, depending on the needs of the mission at that time. The mission will be using a sequence length of one month during early interplanetary cruise, and until the end of the SEP portion of the mission. During the post-SEP ballistic cruise, the command sequences will be bimonthly. Sequences during the Saturn Tour Phase will again be monthly. However, since science during Titan orbit is planned around a number of 16 day science campaigns, the TSSM sequencing schedule will be changed to a 16 day sequence after TOI.

4.5.1.3 Science Planning, Analysis, and Archive

Science teams perform analysis of the returned science products. The analysis would be used to support future data collection strategies and to guide the longer-range observation plan updates. Further discussion on science planning can be found in §2.4.6.

The science planning team develops all instrument and most pointing command sequences. These sequences are verified and loaded by the mission operations team.

All mission science data, from both US and international instrument teams, will be archived in the Planetary Data System (PDS).

4.5.1.4 Interface to ESA Ground System

The Flight System will carry the *in situ* elements for deployment to Titan, and also provide support for these elements. The ground system will also provide an interface to the ESA ground system that will be used to control and operate these *in situ* elements. As can be seen in **Figure 4.5-1**, the ESA ground system will interface directly with the multi-mission portion of the ground system. Furthermore, as shown in **Figure 4.5-2**, telemetry from the *in situ* elements is sent from the telemetry capture function directly to the ESA ground system for the operations of the *in situ* elements. Commands for these *in situ* elements will be sent directly to the command system in the multi-mission systems.

Current baseline for this mission is to use the disruption tolerant networking protocols to provide the connectivity between the *in situ* flight elements and the ESA ground system. These techniques and technologies should reduce the role of the TSSM ground system and the spacecraft to simple data routers in the path between the *in situ* flight elements and their ESA ground system. The first flight demonstration of the disruption tolerant networking protocols is currently scheduled to occur during the first quarter of FY09. As this report is written, this flight demonstration is in its final testing cycle. However, if it is deemed that the disruption tolerant protocols are not sufficiently developed for use in the TSSM mission, then the fall back plan would be to use the techniques and procedures that have been in use since early 2004 to operate the Mars Exploration Rovers and the Phoenix lander on Mars. No matter what protocols and techniques are used to communicate between the *in situ* elements and their ESA ground system via the TSSM spacecraft and ground system, special care will be required to ensure that the commands forwarded to the *in situ* elements do not interfere, in any way, with the operation of the orbiter.

4.5.2 Ground System during the TSSM Mission

The following discussion provides an overview of how the Ground System will be used during all of the major phases of the TSSM mission.

4.5.2.1 DSN Scheduling Rationale

The amount of tracking for this mission is significant due to the duration of the mission and the science volumes collected at Titan and during the Saturn tour. The mission duration of 13 years and major mission phases are illustrated in **Figure 4.5-3**. The DSN tracking profile used for the current trajectory is summarized in **Table 4.5-1**. The profile, like the trajectory, is notional and provided only as a way of demonstrating the proof-of-concept, both will change and evolve over the course of project development.

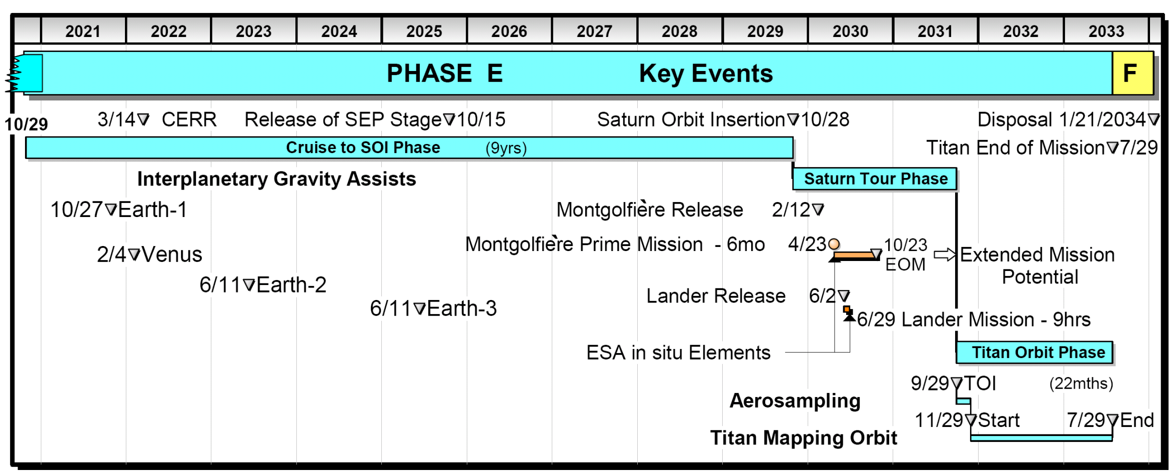


Figure 4.5-3. Baseline Titan Saturn System Mission phase timeline.

4.5.2.2 Launch and Early Operations

Immediately after launch an intense month of Flight System deployment, checkout, and critical maneuvers. This period will use round-the-clock tracking by the DSN 34 m subnet to support the commanding, Flight System telemetry, and RF navigation data needed for these tasks. During this phase the Flight System developers are monitoring the deployments and performing their final in space tests and handing the Flight System over to the flight team. The navigation team compares the actual launch performance versus the predicted, reviews RF data and alters the maneuver design to ensure the Flight System will achieve the planned trajectory that will take it to Saturn, and finally Titan.

4.5.2.3 Interplanetary Cruise

The duration of cruise drives the tracking to be economical and still ensure safe delivery to Saturn orbit. During SEP operations tracking will be similar to what Dawn is currently using: one 8 hour pass per week, with an additional ΔDOR pass every other week for the duration of thrusting. While the SEP is not in use tracking will be reduced to one 8 hour pass every other week, with quarterly light instrument checkouts. Flybys will also be used to test science and instrument operating procedures, in early preparation for the Saturn tour.

About 18 months before SOI, tracking frequency is increased to handle the operational needs for SOI and the tour. This tracking will be used for flight software loads and provide RF tracking data to support increased orbit determination and trajectory analysis work for SOI, as well as some early Saturn system science. Approach to SOI is accompanied by significantly increased tracking including ΔDOR.

4.5.2.4 Saturn Tour

Once in Saturn orbit, tracking goes to a steady state of daily 8 hour 34 m passes, intended to support Saturn system science data collection and navigation. This routine is augmented around flybys to support the final navigation analysis and increased science. During and right after each flyby, tracking frequency should be increased to maximize science return and improve navigation analysis accuracy. The Saturn Tour Phase also marks the mission phase when the majority (if not all) of the Titan *in situ* data will be relayed back to Earth. Current analyses indicate that this amount of tracking will comfortably provide sufficient downlink data volume for flyby science at Titan and Enceladus.

4.5.2.5 Titan Aerobraking and Mapping

The tour ends with Titan orbit insertion. Once in orbit, DSN tracking is increased to near-continuous tracking for the 2 month Aerobraking Phase. This is for navigation purposes, as well as radio science. Once the Aerobraking Phase is complete, two 8 hour DSN tracks per day will be required for much of the 20 month prime orbital mission.

In addition to the instrument based science observations, Titan gravity science will be performed during as many of the Titan aerobraking and mapping (science) orbits as possible using the radio science capabilities of the Flight System and DSN. Gravity science, as described, will use coherent, two-way (uplink and downlink) Ka- and X-band Doppler data. Currently, Goldstone’s 34 m BWG, DSS-25 is the only antenna in the DSN that has or is planned to have a Ka-band transmitting capability.

Current analyses indicate that this amount of tracking will comfortably provide sufficient downlink data volume for aerobraking and Titan mapping science.

4.5.2.6 End of Mission

The details of the spacecraft disposal trajectory with Titan are still being worked. It is possible to acquire science data until the spacecraft impacts at a safe location.

4.5.2.7 Extended Titan Science

If an extended mission is approved, the Circular Orbit Phase could be continued for years until the Flight System is on the verge of inoperability or until the project is terminated.

4.6 Operational Scenarios

4.6.1 Operating in Titan Orbit

For many reasons, Saturn’s moon, Titan, has long been a darling of the science community. With its dense atmosphere of nitrogen and methane, and a surface covered with organic material, it is Titan that is arguably Earth’s sister world.

Many of the science highlights from the Cassini-Huygens mission were gathered during its limited number of high-speed (~6 km/s)

Titan flybys. When attempting to uncover and understand a world as complex as Titan, the advantages of operating from a stable orbit are clear. During the 20-month Circular Orbit Phase, the spacecraft will collect data continuously. The result will be a wealth of information that reveals Titan and answers long-held questions about Titan's interior, surface, atmosphere, and the complex interaction with Saturn's magnetosphere.

Operations during both the Saturn Tour Phase and the Titan Orbital Phase will benefit from the fact that much of the Saturnian system ephemeris data (masses, radii, orbital periods, etc.) are already well understood from Cassini-Huygens. There is also significant knowledge of Titan's atmosphere at high altitudes; finding and maintaining good quality mapping orbits should not be a significant challenge. With the operational environment already well understood, operational complexity (and, in turn, operations cost) will be reduced.

4.6.2 Mission Scenarios Overview

The concept of operations completed in this section demonstrates a strategy that meets the data return requirements for the science measurements. There is sufficient margin to increase data rates in several parts of these scenarios. Excess capacity, and how best to utilize it, will be determined once the final instruments are determined.

The mission has been divided into four phases: Interplanetary Cruise, Saturn Tour, Titan Orbit, and Decommissioning and Disposal. An overview of the science operations for each of these is given below. The bulk of the science data acquisition will occur during the Saturn Tour and Titan Orbit Phases; detailed operational scenarios have been developed for each of these and can be found in §4.6.3.1 and §4.6.3.2, respectively. **Figure 4.6-1** shows the mission phases and timeline.

To reduce cost, the mission will minimize the level of operations activity during cruise. This will include the use of hibernation-type modes as demonstrated on New Horizons. However, limited observations will be allowed during gravity assist flybys for payload instrument calibrations and flight team training. A discussion of instrument calibrations is included in §4.2.1.1. This, and other recommendations from the "Mission Operations Lessons Learned Study for The Next Outer Planets Flagship (OPF) Mission" were put in place.

Saturn Orbit Insertion will occur ~9 years after launch and will mark the beginning of the Saturn Tour Phase. The Saturn Tour Phase will allow the spacecraft's potent set of instruments valuable opportunities to observe Titan, Enceladus, and Saturn's magnetosphere, as never before. During the 24 month Saturn Tour Phase, the spacecraft will perform 16 Titan and seven Enceladus flybys. The Saturn Tour Phase also marks the mission phase when the Titan *in situ* data will be relayed back to Earth.

The Titan Orbit Phase begins with TOI and includes a two month period of aerobraking followed by 20 months in circular orbit at 1500 km altitude.

Near the end of mission, the Decommissioning and Disposal Phase will put the orbiter on a trajectory spiraling slowly downward through the Titan atmosphere. Any areas of planetary protection concern on Titan's surface will have been identified and will be avoided. This phase is expected to last six months; the decaying orbit will provide extraordinary opportunities for atmospheric and surface observations.

Some of the assumptions that went into the formulation of these scenarios include: four operational ASRGs (this assumes one of the five is a spare), a 35 W TWTA with an average playback rate of 140 kbps, and a 32 Gb SSR. There is also a 700 W-hr rechargeable battery that can be invoked for limited periods of time. The allowable depth-of-discharge for the battery was assumed to be 40%.

All of the scenario modeling was also done assuming the more conservative power case of five MMRTGs. If directed, the use of MMRTGs is a viable option, and the science operations as discussed in this section will not be degraded.

Some of the science instruments have a variety of data rates; the range of rates is listed in **Table 4.2-2**. A rate of 77 kbps (300 kbps uncompressed) is given for the HiRIS Imager. It should be noted that this rate is for a single band/color, and the instrument has the ability to collect data in three bands simultaneously (i.e., 900 kbps). This analysis assumes the

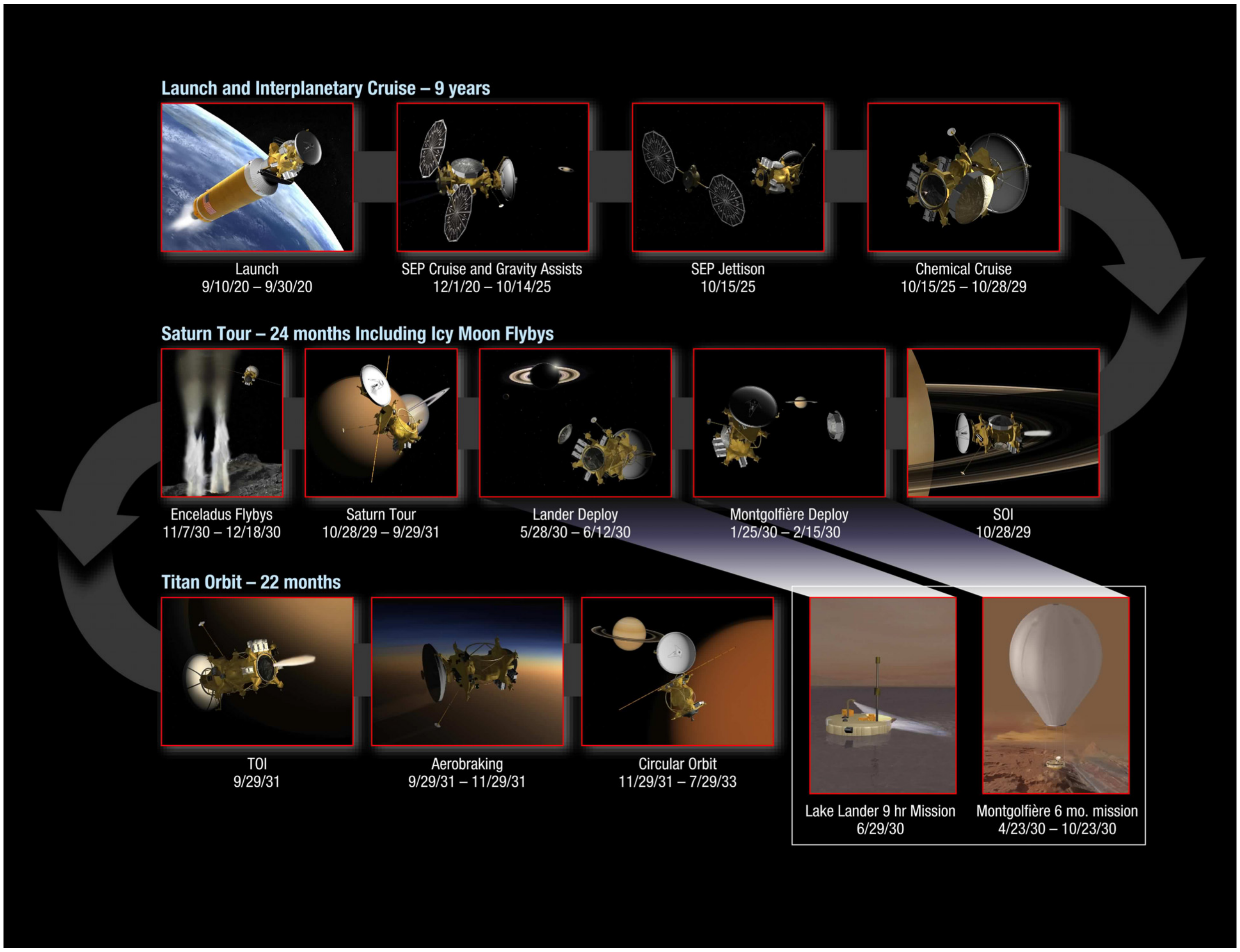


Figure 4.6-1. *TSSM mission phases and timeline.*

900 kbps rate only for Enceladus flybys because of the uniqueness of those opportunities.

Tour Flybys and Instrument Fields of View

The instrument mounting locations, orientations, and fields of view were chosen to optimize science data collection during the Circular Orbit Phase of the mission. **Figure 4.2-1** shows the instrument placements and fields of view. The remote sensing (RS) and sounders are all aligned with the spacecraft '-X' direction and will be nominally nadir pointed while in Titan orbit. The spacecraft will carry two TiPRA antennas. The first will be deployed after SOI and will be used to measure the ice thickness at Enceladus. Prior to TOI, that boom will be ejected. The second TiPRA antenna will be deployed once the spacecraft is in circular orbit at Titan. Each TiPRA antenna is a dipole antenna that consists of two 5 m booms extending in opposite directions. TiPRA can gather data simultaneously with the other RS and sounder instruments. The fields and particle instruments all benefit from a '+Y to ram' attitude. This configuration will also prove to be advantageous during the Titan and Enceladus flybys by allowing groups of instruments to gather data simultaneously.

The majority of instruments will be fully operational for the high-priority hours around the Titan and Enceladus flybys. The additional power needed will be provided by commanding telecom to standby mode and making use of the on-board rechargeable battery. For at least one of the seven Enceladus flybys, telecom will remain operational so that radio science can take measurements of the Enceladus gravity field and internal structure.

For each low Enceladus and Titan flyby, the spacecraft attitude will be optimized for the RS and sounder instruments (i.e., point '-X' toward Titan/Enceladus), except for the several

minutes around closest approach. The attitude during this period will be '+Y to ram' so that the fields and particles instruments are in position to sample and characterize the chemistry of the Enceladus plume and Titan's atmosphere. Using the current instrument data rates, each Enceladus flyby will collect ~15 Gb of science data that will be compressed to 3.75 Gb and played back over a 6.5 hr period immediately following the encounter. Each Titan flyby will collect ~26 Gb of science data that will be compressed to 6.5 Gb and played back over two 7 hr downlink periods following each encounter. These downlink durations assume the use of a 34 m DSN antenna and a conservative 140 kbps rate. This is well within the telecom system's capabilities (see Appendix C).

Also during the Saturn Tour Phase, the two *in situ* vehicles will perform their prime mission activities. The montgolfière will be released from the orbiter during the first Titan encounter, and the lander on the following Titan pass. The prime mission is expected to be six months for the montgolfière and nine hours for the lander. The data from the montgolfière will be recorded, sent to the orbiter when in view, and then relayed back to Earth. During the first few hours of its mission, the lander will store its science data on its SSR. The data link capability to the orbiter increases significantly after a few hours and all of the lander data (recorded and real-time) will be sent to the orbiter, and then relayed back to Earth. The data return strategy is discussed in §4.6.4 and **Foldout 5** (**FO-5**).

Titan Orbit Phase

The Titan Orbit Phase begins with Titan Orbit Insertion (TOI) and a two-month Aerobraking Phase. The ~200 aerobraking passes will yield data from deep in Titan's atmosphere (as low as 600 km altitude), hundreds of kilometers lower than the Cassini orbiter ventured. Once the spacecraft has settled into its 1500 km orbit, the suite of instruments will carry out specific campaigns that will drastically enhance our understanding of Titan and how it functions as a system.

During the 20 month Circular Orbit Phase, the spacecraft will collect data continuously. Three different types of science campaigns, each designed to manage power and data rate, will be used to gather a wealth of information that will fully reveal this world and answer long-held questions about Titan's interior, surface, atmosphere, and interaction with Saturn's magnetosphere. Each campaign, or instrument combination, will be maintained for 16 days (one Titan revolution) and they are as follows:

1. Atmosphere and Ionosphere Campaign to identify and measure ions and neutrals globally for various Sun angles (PMS and MAPP).
2. Surface Map Campaign during which a global map (in up to four colors) is obtained, to measure global altimetry with better than 10 m accuracy and perform surface spectrometry (HiRIS, TiPRA, and MAPP).
3. Atmospheric Dynamics and Composition Campaign to measure temperatures, composition, and winds, globally (TIRS and SMS).

Figure 4.6-2 illustrates how these campaigns may be used in succession to capture the Titan Orbit Phase science objectives. The spacecraft will complete 80 orbits during each 16 day campaign.

Throughout the Titan Orbit Phase, the radio science investigation (RSA) will collect data at the DSN on every downlink. The assumed operational scenarios for the Circular Orbit Phase are detailed in §4.6.3.2.

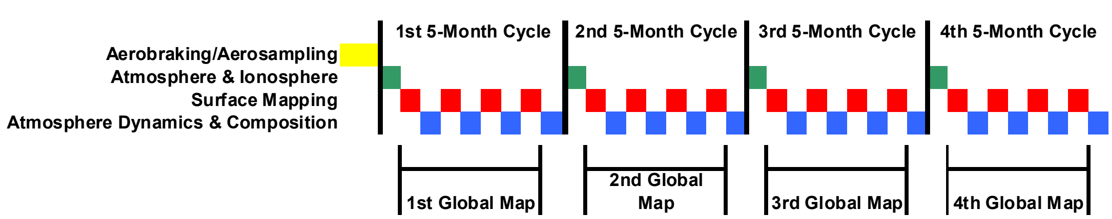
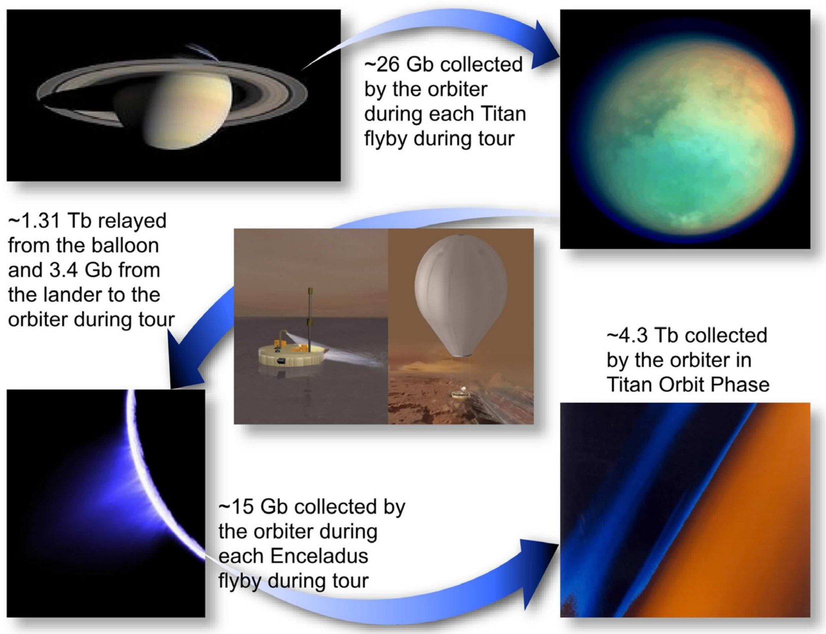
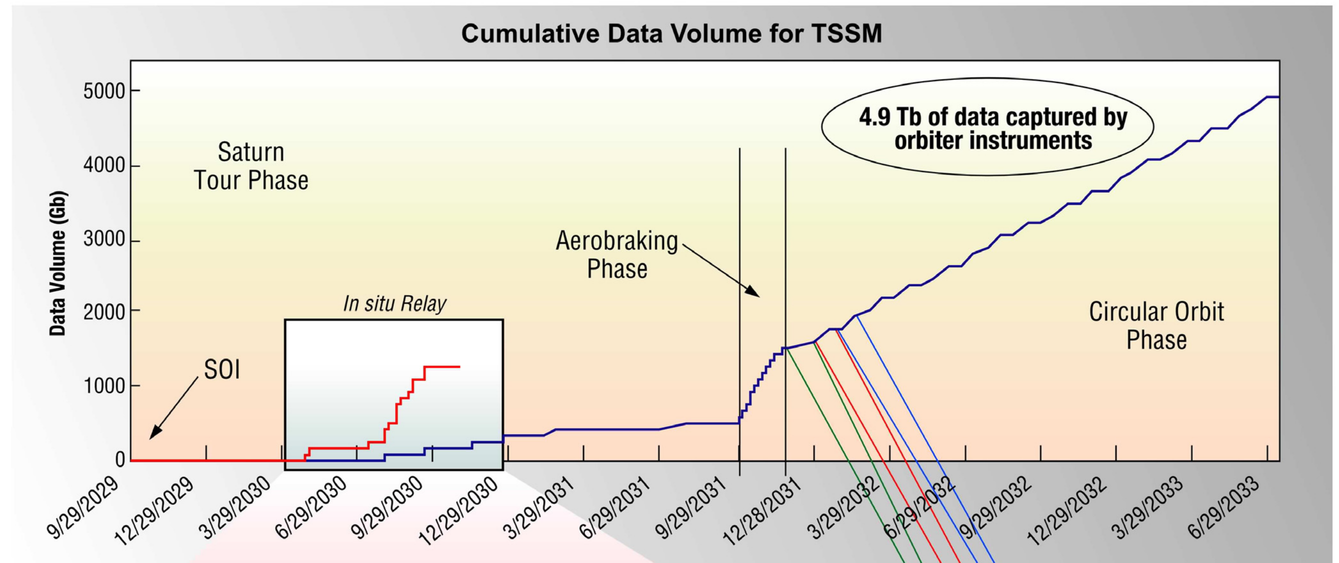


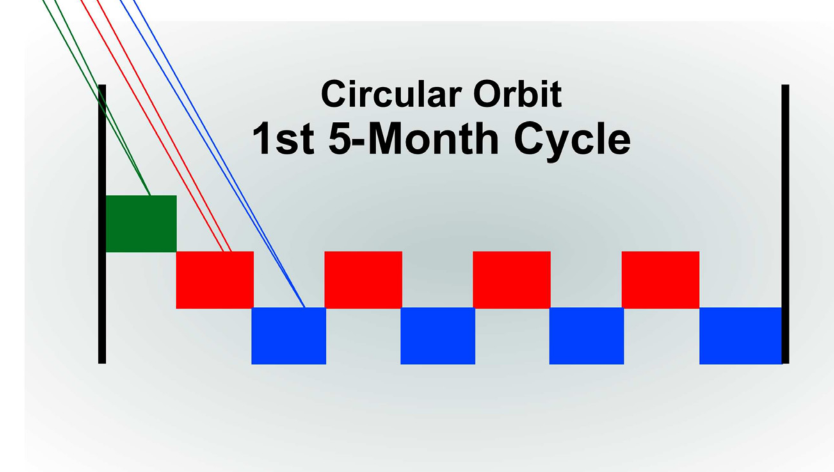
Figure 4.6-2. *Campaigns are arranged in 5-month cycles comprising nine periods of sixteen-day campaigns.*



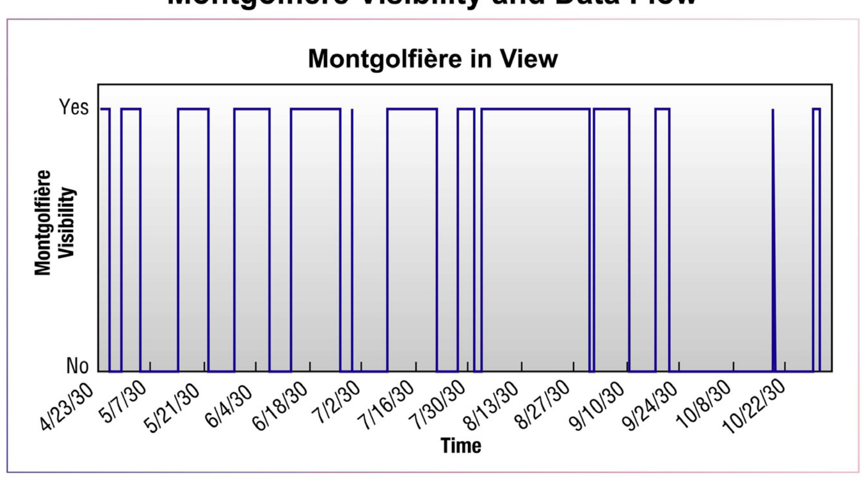


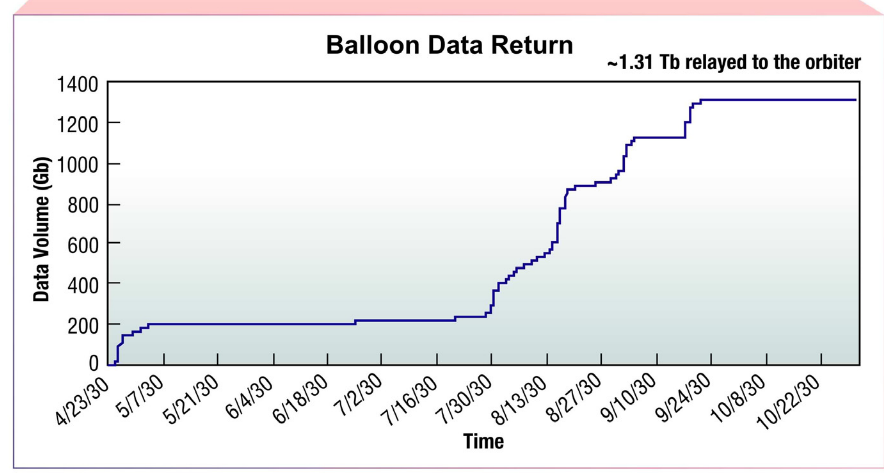
Orbital Campaigns

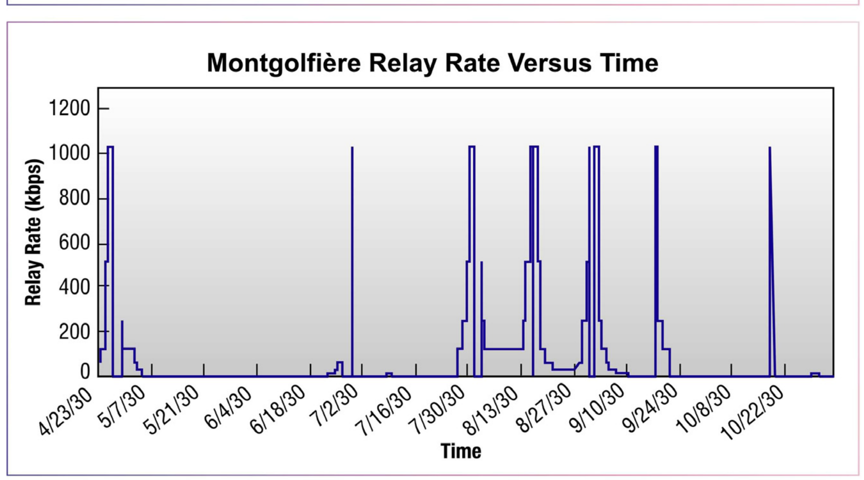
- Atmosphere and ionosphere (**PMS** and **MAPP**): Identify and measure ions and neutrals globally for various Sun angles. Each of these 16 day campaigns collects 48.3 Gb.
- Surface map (**HiRIS, TIPRA,** and **MAPP**): Global map in up to four colors; global altimetry with better than 10-m accuracy; surface spectroscopy. Each of these 16 day campaigns collects 475 Gb.
- Atmosphere dynamics and composition (**TIRS** and **SMS**): Measure temperatures, composition, and winds, globally. Each of these 16 day campaigns collects 36.5 Gb.



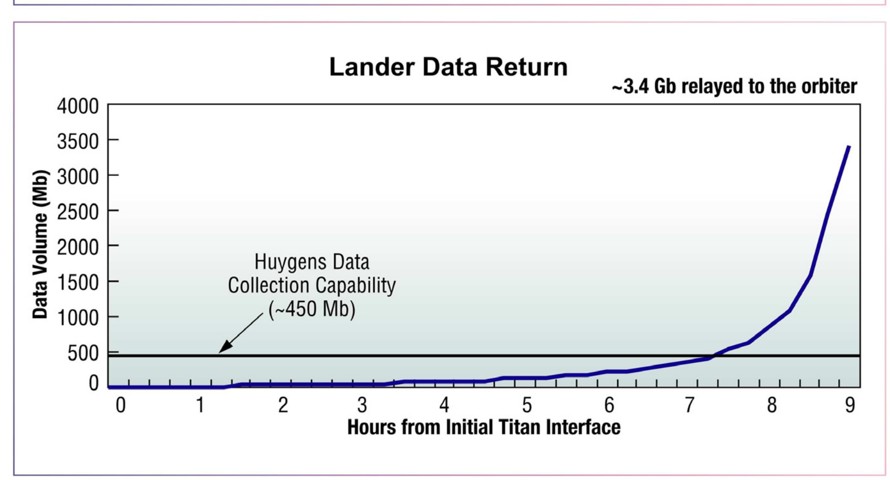
Montgolfière Visibility and Data Flow

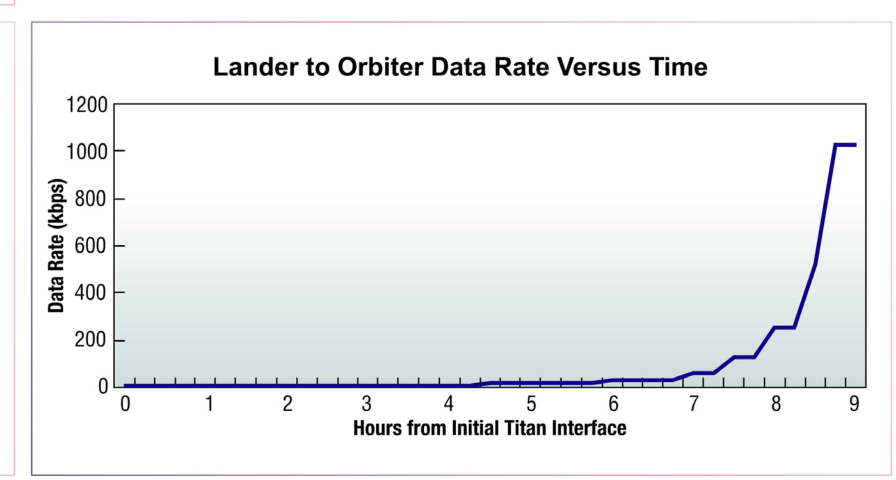






Peaks coincide with Titan flybys.





4.6.3 Scenario Descriptions

4.6.3.1 Saturn Tour Phase

Saturn Orbit Insertion will occur ~9 years after launch and will represent the start of the Saturn Tour Phase of the mission. This 24 month period will provide scientists with a range of targets to gain understanding of Titan's role in the Saturnian system. During the Saturn Tour Phase the orbiter will collect data throughout Saturn's magnetosphere, focusing on its interaction with Titan and Enceladus. This section focuses on the data capture scenarios for the 16 Titan and seven Enceladus flybys, as well as the *in situ* data relay.

Data Capture from the In Situ Vehicles

The geometry of the *in situ* vehicle communication is shown in **FO-1**. The relay of the *in situ* vehicle data is described in §4.6.4 and in **FO-5**. The montgolfière will be released on approach to the first Titan flyby and the lander will be released on the following Titan pass. For the lander, the orbiter will be in communication for approximately nine hours before the orbiter crosses Titan's horizon. During those nine hours, the lander may send as much as 3.4 Gb of high-value data to the orbiter. This data will be relayed back to Earth multiple times to ensure its safe return.

The prime mission duration for the montgolfière is six months. For the majority of the Saturn Tour Phase, the orbiter-to-montgolfière distance will be between 1 and 3 million km, and often this distance will be less than 1 million km. The montgolfière-to-orbiter data rate as a function of time is shown in **FO-5**.

A plot showing the montgolfière visibility and data flow is also shown in **FO-5**. A total of 1.3 Tb may be relayed from the montgolfière to the orbiter and back to Earth over the montgolfière's six-month prime mission. It is recognized that the life of the montgolfière may well extend through the end of the Saturn Tour Phase and even into the Circular Orbit Phase of the mission. The science scenarios during the Circular Orbit Phase have margin in the data flow; the orbiter will be capable of capturing the montgolfière data as well as its own orbital science.

Scenarios were devised for the Titan Orbital Phase based on science discipline and the need to budget the individual instruments' operating times. For flybys, creating workable scenarios is also a non-trivial matter, as multiple instruments will be competing for valuable observing time and spacecraft resources.

If additional power is needed, there is a 700 W-hr rechargeable battery on board that can be invoked for limited periods of time before it must be charged back to capacity. Also, for limited periods, the telecom system can be placed in standby mode to save additional power. The 32 Gb solid state recorder (SSR) allows science operations to continue for extended periods without downlinking (i.e., with telecom in standby). However, several of the science goals pertaining to Enceladus, in particular, involve the use of the telecom system for Radio Science measurements.

Enceladus Flybys

Two data acquisition scenarios for Enceladus flybys are shown in **Table 4.6-1** and **Table 4.6-2**. For the seven planned Enceladus flybys (100 km to 1100 km), these scenario timelines illustrate that Enceladus-related mission objectives can be met. The time near closest approach is dedicated to direct sampling of the environment, in particular the south polar plume. Also, TiPRA will operate in sounder mode for the several minutes around closest approach. Outside of the 20 minutes around closest approach is prime opportunity for high resolution imaging and IR spectrometry.

The first of the two Enceladus flyby scenarios, E1, has all of the instruments operating simultaneously (except Radio Science) for the four-hour period around closest approach (shown in **Table 4.6-1**). The 700 W-hr battery may be invoked during this period resulting in a discharge of 8%. For Scenario E1, battery recharge needed would begin two hours after closest approach. This will entail putting multiple instruments in standby mode until the power system is nominal and downlink can begin.

Table 4.6-2 describes the Radio Science option, E2. All instruments (except SMS and TIRS) obtain data in this four-hour scenario, but the planning has been optimized for Radio Science. Operating in this manner for the four hour period around Enceladus closest approach, with telecom operational, results in a battery discharge of ~33%. The battery recharge will begin two hours after closest.

Table 4.6-1. *Enceladus flyby, E1 (telecom in standby).*

Instruments Operating in Scenario:	HiRIS	TIPRA	SMS	TIRS	PMS	MAPP	RSA
	ON	ON	ON	ON	ON	ON	OFF

Flyby Time

Time (Relative to Closest Approach)	Highlights	Spacecraft Pointing	Approximate Range to Enceladus	Comments
-2 hr to -10 min	High resolution imaging; Near & mid IR mapping spectrometry	*RS (-X) to Enceladus	35,000 to 3,000 km	-
-10 min to +10 min (Closest Approach)	Direct sampling mass spectrometry; Ice thickness measurements	PMS (+Y) to ram	~100 km at Closet Approach	-
+10 hr to +2 hr	High resolution imaging; Near & mid IR mapping spectrometry	*RS (-X) to Enceladus	~3,000 to 35,000 km	-
+2 hr to +3 hr	Battery recharge before telecom system turns on	-	-	Select instruments to standby mode
+3 hr to +9 hr	Downlink to 34 m DSN	-	-	Assumed rate is 140 kbps; Select instruments stay in standby mode

Remote Sensing Instruments are Prime
Fields & Particles Instruments are Prime
Downlink Data to Earth

* RS = Remote Sensing Fields of View (HiRIS, TIPRA, SMS, TIRS)

Total of 15 Gb of uncompressed data collected.

Telecom in standby until +3 hr.

MAPP collects at high data rates throughout the encounter.

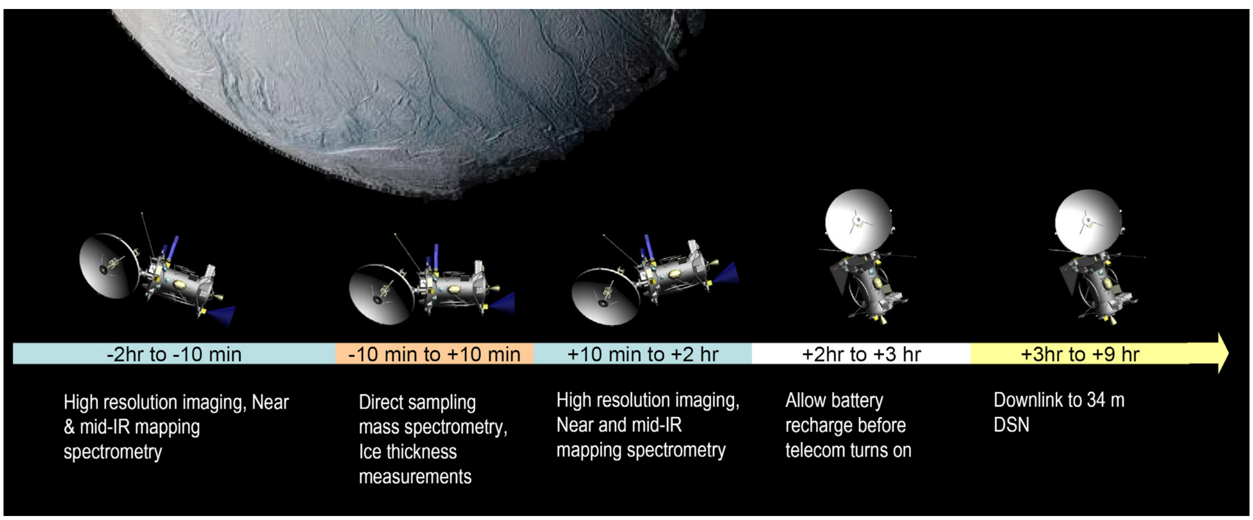


Table 4.6-2. *Enceladus flyby, E2 (radio science option).*

Instruments Operating in Scenario:	HiRIS	TIPRA	SMS	TIRS	PMS	MAPP	RSA
	ON	ON	OFF	OFF	ON	ON	ON

Flyby Time

Time (Relative to Closest Approach)	Highlights	Spacecraft Pointing	Approximate Range to Enceladus	Comments
-2 hr to -10 min	Radio Science gravity field measurements; High resolution imaging; Near & mid IR mapping spectrometry	*RS (-X) to Enceladus, HGA articulated to Earth	35,000 to 3,000 km	-
-10 min to +10 min **(Closest Approach)**	RSA gravity field measurements; Direct sampling mass spectrometry; Ice thickness measurements	PMS (+Y) to ram; HGA articulated to Earth	~100-400 km at Closest Approach	-
+10 min to +3 hr	Radio Science gravity field measurements; High resolution imaging; Near & mid IR mapping spectrometry	*RS (-X) to Enceladus, HGA articulated to Earth	3,000 to 35,000 km	-
+3 hr to +9 hr	Downlink to 34 m DSN	-	-	Assumed rate is 140 kbps

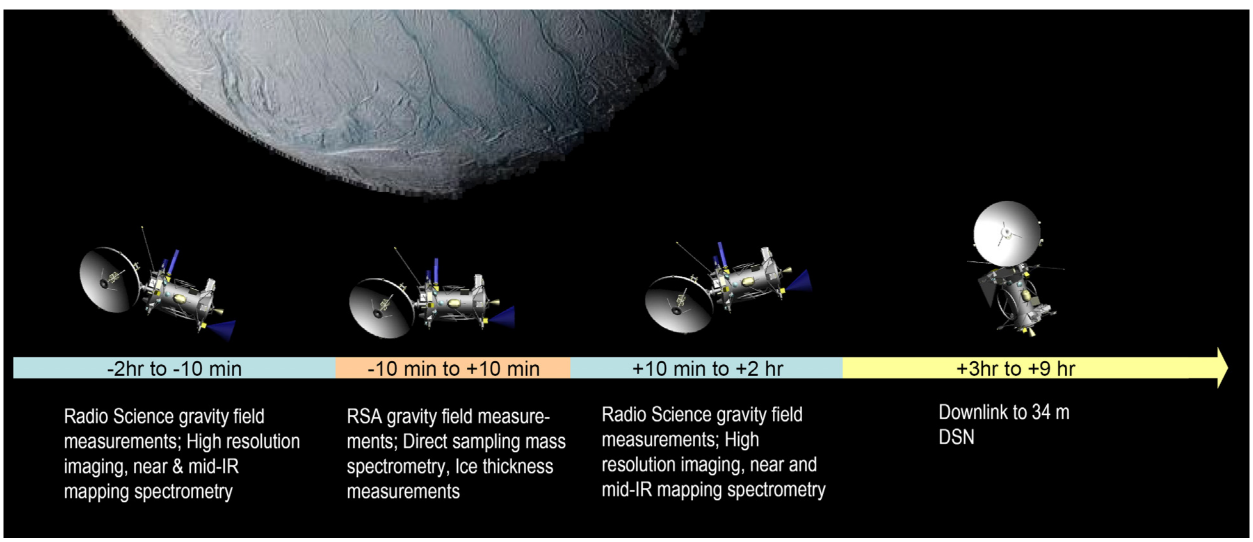
Remote Sensing Instruments are Prime
Fields & Particles Instruments are Prime
Downlink Data to Earth

*** RS = Remote Sensing Fields of View (HiRIS, TIPRA, SMS, TIRS)**

Total of 15 Gb of uncompressed data collected.

Telecom operational throughout encounter.

MAPP collects at high data rates throughout the encounter.



approach and will involve multiple instruments transitioning to a non-operational mode.

The E1 type of Enceladus flyby will collect ~15 Gb of data toward the following science objectives:

1. Characterizing the chemistry of the Enceladus plumes.
2. Testing for true polar wander on Enceladus (to infer internal structure).
3. Understanding the formation of the active region near the south pole, and whether liquid water exists beneath the area.
4. Direct measurement of Enceladus' ice thickness
5. Identifying and characterizing candidate sites on Enceladus for future *in situ* exploration

The E2 type of Enceladus flyby will collect ~15 Gb of data toward the following science objectives:

1. Inferring the internal structure of Enceladus, including gravity anomalies
2. Characterizing the chemistry of the Enceladus plumes.
3. Testing for true polar wander on Enceladus (to infer internal structure).
4. Understanding the formation of the active region near the south pole, and whether liquid water exists beneath the area.
5. Direct measurement of Enceladus' ice thickness
6. Identifying and characterizing candidate sites on Enceladus for future *in situ* exploration.

Titan Flybys

There will also be 16 flybys of Titan during the 24 month Saturn Tour Phase. Eight of these flybys will be low (720 to 1240 km). The data acquired from these passes will not only be valuable to science, but it will also be used by mission engineers to characterize Titan's atmosphere near the aerobraking altitudes. The remaining eight Titan flybys will occur at altitudes of 1820 km to 3480 km. During the low flybys, the spacecraft attitude around closest approach will be optimized for PMS and MAPP instruments (**Table 4.6-3**). The altitude around the closest approach of higher flybys will be optimized for imaging (**Table 4.6-4**).

During the Titan flybys and the Titan Aerobraking Phase, the SMS and TIRS teams will use the periods of higher altitudes to observe Titan's limb. High altitudes also afford a prime opportunity for cloud observations and global imaging. In addition, there will be a limited window near closest approach where the spacecraft attitude is optimal for all of the instruments (+Y to ram, -X to Titan)—Remote Sensing (RS) and Fields and Particles (F & P).

For these two Titan flyby scenarios, certain instruments were selected for standby mode for various passes in order to manage spacecraft power. Science negotiations may result in a different set of instruments being operational during a flyby. For example, HiRIS is likely to be operational only on the inbound or outbound leg of the flyby, not both, upon which portion of Titan is lit by the Sun.

Two data acquisition scenarios for Titan flybys are shown in **Table 4.6-3** and **Table 4.6-4**. The time period chosen around closest approach can be extended easily. There are specific observations that can be better made during these low flybys that can be made in the 1500 km Circular Orbit Phase. Data taken during these flybys will be compared to that taken during the Circular Orbit Phase to assess seasonal changes on the surface and in the atmosphere.

The Titan flybys during the Saturn Tour Phase will collect ~26 Gb of data toward the following science objectives:

1. Characterizing the atmospheric circulation and flow of energy over seasonal variations.
2. Determining how energy is deposited in the upper atmosphere to drive the chemistry and the escape rate of major atmospheric constituents.
3. Characterizing the relative importance of exogenic and endogenic oxygen sources.
4. Characterizing the major processes controlling the global distribution of atmospheric chemical constituents.
5. Characterizing the major processes transforming the surface throughout time.

Table 4.6-3. Titan flyby, T1 altitude example.

Instruments Operating in Scenario:	HiRIS	TIPRA	SMS	TIRS	PMS	MAPP	RSA
	ON	OFF	ON	ON	ON	ON	OFF

Flyby Time

Time (Relative to Closest Approach)	Highlights	Spacecraft Pointing	Approximate Range to Titan	Comments
-5 hr to -2 hr	Global imaging; Cloud mapping; Near & mid IR mapping spectrometry	*RS (-X) to Titan	60,000 to 20,000 km	-
-2 hr to -30 min	High resolution imaging; IR mapping spectrometry; Observe Titan/magnetosphere interaction	*RS (-X) to Titan	20,000 to 6,000 km	-
-30 min to +30 min (Closest Approach)	Direct sampling mass spectrometry	PMS (+Y) to ram	~850 km at Closest Approach	-
+30 min to +2 hr	High resolution imaging; IR mapping spectrometry; Observe Titan/magnetosphere interaction	*RS (-X) to Titan	6,000 to 20,000 km	-
+2 hr to +5 hr	Global imaging; Cloud mapping; Near & mid IR mapping spectrometry	*RS (-X) to Titan	20,000 to 60,000 km	-
+5 hr to +6hr	Battery recharge before telecom system turns on	-	-	Select instruments to standby mode
+6 hr to +20 hr (or two 7 hr passes)	Downlink to 34 m DSN	-	-	Assumed rate is 140 kbps; Select instruments stay in standby mode

Remote Sensing Instruments are Prime
Fields & Particles Instruments are Prime
Downlink Data to Earth

* RS = Remote Sensing Fields of View (HiRIS, TiPRA, SMS, TIRS)

Total of 26 Gb of uncompressed data collected.

Telecom in standby until +6 hr.

MAPP collects at high data rates throughout the encounter.

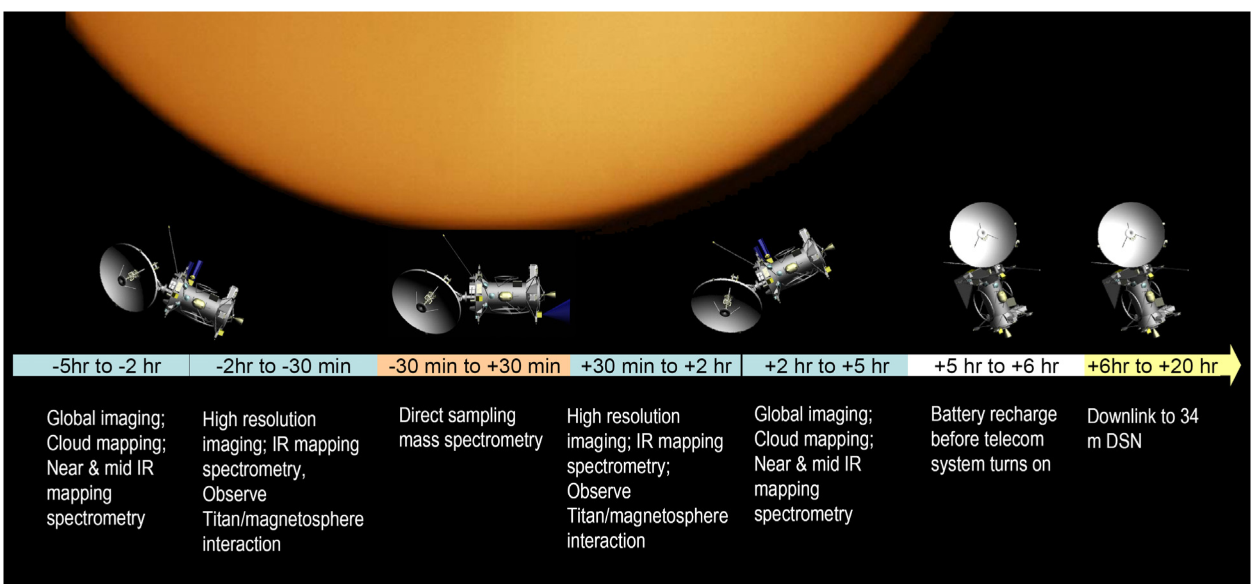


Table 4.6-4. *Titan flyby, T2 (higher-altitude example).*

Instruments Operating in Scenario:	HiRIS	TIPRA	SMS	TIRS	PMS	MAPP	RSA
	ON	OFF	ON	ON	ON	ON	OFF

Flyby Time

Time (Relative to Closest Approach)	Highlights	Spacecraft Pointing	Approximate Range to Titan	Comments
-10 hr to -2 hr	Limb sounding; IR mapping; Cloud imaging; Global mapping	*RS (-X) to Titan	125,000 to 20,000 km	-
-2 hr to +2 hr (Closest Approach)	High resolution imaging; IR mapping spectrometry; Observe Titan/magnetosphere interaction	*RS (-X) to Titan	20,000 to 6,000 km at Closest Approach	-
+2 hr to +10 hr	Limb sounding; IR mapping; Cloud imaging; Global imaging	SMS to Titan limb	6,000 to 20,000 km	-
+10 hr to +11 hr	Battery recharge before telecom system turns on	-	20,000 to 125,000 km	Select instruments to standby mode
+11 hr to +20 hr (or two 7 hr passes)	Downlink to 34 m DSN	-	-	Assumed rate is 140 kbps; Select instruments stay in standby mode

Remote Sensing Instruments are Prime
Fields & Particles Instruments are Prime
Downlink Data to Earth

* RS = Remote Sensing Fields of View (HiRIS, TiPRA, SMS, TIRS)

Total of 26 Gb of uncompressed data collected.
Telecom in standby until +11 hr.
MAPP collects at high data rates throughout the encounter.

4.6.3.2 Titan Orbit Phase

Aerobraking

The Titan Orbit Phase begins with Titan Orbit Insertion (TOI) and a two month aerobraking period. There will be approximately 200 aerobraking passes over the two months. The altitude at TOI will be 720 km and subsequent passes may decrease to as low as 600 km. Eventually, each Titan periapse altitude will increase until the 1500 km circular orbit is reached. The period of the first orbit will be ~20 hours and will decrease until the stable orbit is reached; at which point the orbit period will be 287 min. Near-continuous DSN coverage, and in turn, a near-continuously operating telecom system, has been assumed for the Aerobraking Phase. There will be a period around each periapse where the HGA is used in aerobraking—communication with Earth will not be possible at these times.

The data gathered at the low-altitude aerobraking passes will be highly coveted. This is not only true for atmospheric observations, but also for our desire to understand Titan's interior and whether or not it has a dynamo. With the telecom system operational throughout most of the Aerobraking Phase, power will be restricted. Generally, each aerobraking scenario will be optimized for PMS and MAPP when the spacecraft is in the atmosphere and optimized for HiRIS, TIRS, and SMS when above the atmosphere. A data acquisition scenario timeline for a typical aerobraking orbit is shown in **Tables 4.6-5** and **4.6-6** and **Figure 4.6-3.** Radio Science will obtain a great deal of data regarding Titan's atmospheric and internal structure during the aerobraking orbits; radio occultations will occur at latitudes ranging from 30° to 60°N and 30° to 60°S.

During the Aerobraking Phase, Scenario A1 will collect ~11 Gb and Scenario A2 will collect ~7.0 Gb of data toward the following science objectives:

Table 4.6-5. *Aerobraking data acquisition, scenario A1.*

Flyby Time

Instruments Operating in Scenario:	HiRIS	TIPRA	SMS	TIRS	PMS	MAPP	RSA
	ON	OFF	OFF	ON	ON	ON	ON

Time (Relative to Closest Approach)	Highlights	Spacecraft Pointing	Approximate Range to Titan	Comments
-5 hr to -30 min	High resolution imaging; Near IR mapping spectrometry	*RS (-X) to Titan	-	-
-30 min to +30 min (Closest Approach)	Direct sampling mass spectrometry	PMS (+Y) to ram	~Varies from 750 to 1500 km	-
+30 min to +5 hr	High resolution imaging; Near IR mapping spectrometry	*RS (-X) to Titan	-	-
For ~3 hr around apoapse	Battery recharge	-	-	MAPP only operational

Remote Sensing Instruments are Prime
Fields & Particles Instruments are Prime

*** RS = Remote Sensing Fields of View (HiRIS, TiPRA, SMS TIRS)**

Total of 10.8 Gb of uncompressed data collected.

Telecom operational as permitted.

MAPP collects at high data rates throughout the encounter.

Table 4.6-6. *Aerobraking data acquisition, scenario A2.*

Flyby Time

Instruments Operating in Scenario:	HiRIS	TIPRA	SMS	TIRS	PMS	MAPP	RSA
	OFF	OFF	ON	ON	ON	ON	ON

Time (Relative to Closest Approach)	Highlights	Spacecraft Pointing	Approximate Range to Titan	Comments
-5 hr to -30 min	Limb sounding; IR mapping	*RS (-X) to Titan	-	-
-30 min to +30 min (Closest Approach)	Direct sampling mass spectrometry	PMS (+Y) to ram	~Varies from 750 to 1500 km	-
+30 min to +5 hr	Limb sounding; IR mapping	*RS (-X) to Titan	-	-
For ~3 hr around apoapse	Battery recharge	-	-	MAPP only operational

Remote Sensing Instruments are Prime
Fields & Particles Instruments are Prime

*** RS = Remote Sensing Fields of View (HiRIS, TiPRA, SMS, TIRS)**

Radio Science obtains gravity and occultation data at various latitudes.

Total of 7.0 Gb of uncompressed data collected.

Telecom operational as permitted.

MAPP collects at high data rates throughout the encounter.

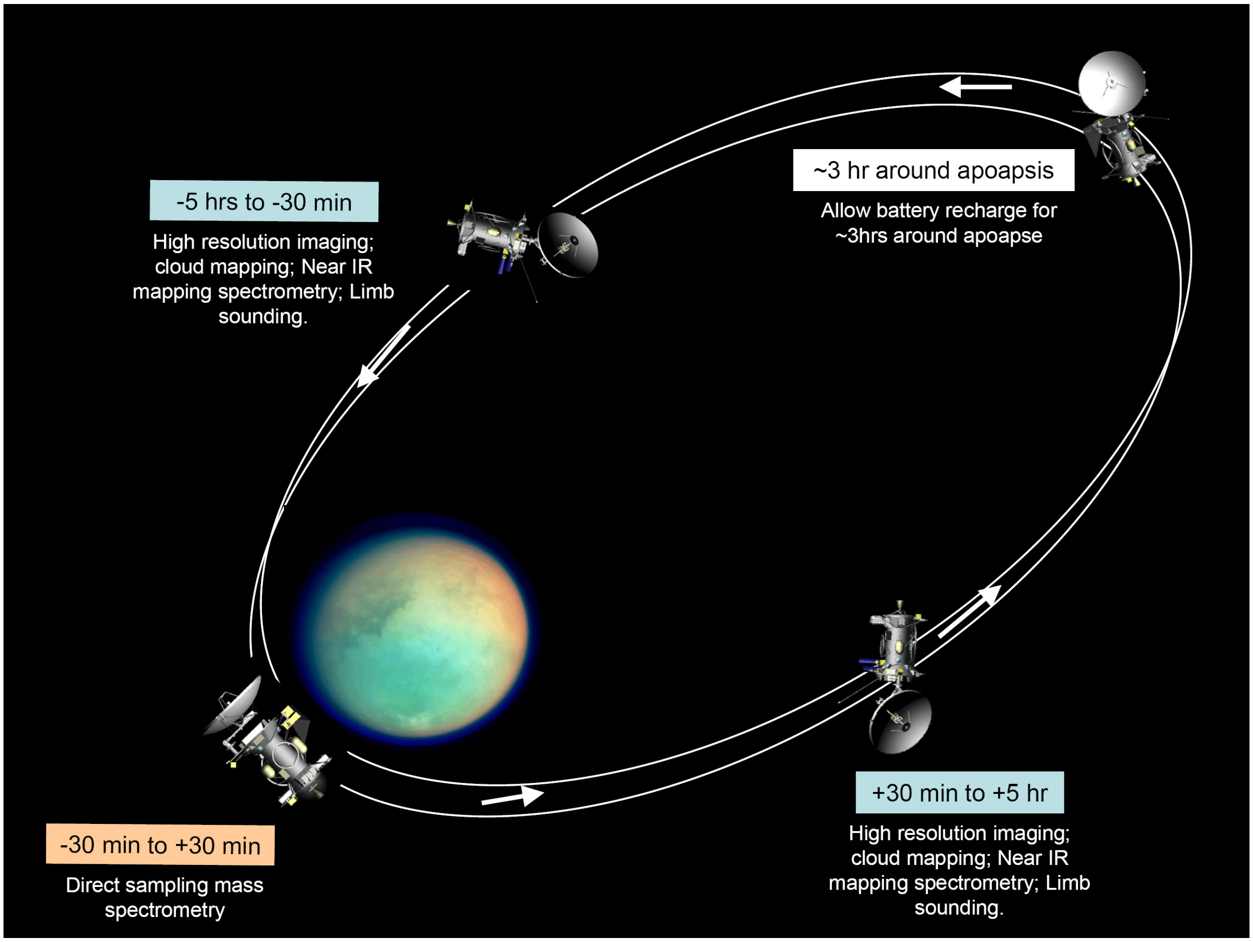


Figure 4.6-3*. General timeline for one of the 200 aerobraking orbits. As the orbit period decreases, the science observation time and required battery rechange duration will be scaled down as well.*

1. Characterizing the major processes controlling global distribution of atmospheric chemical constituents.
2. Determining the atmospheric thermal and dynamical state.
3. Determining the processes leading to formation of complex organics in Titan's atmosphere.
4. Characterizing the atmospheric circulation and flow of energy over seasonal variations.
5. Determining to what level of complexity has pre-biotic chemistry evolved in the Titan system.

With telecom on continuously, science observations will be confined to the 10 hr (+/-5 hr) around Titan periapse. Three hours are needed near apoapse to recharge the battery. If telecom can be commanded to standby for these apoapse periods, then the science specified in the scenario can continue, and the battery will be recharged simultaneously.

These timeline scenarios are for a generic aerobraking orbit with a period of 14 hr or longer. As the orbit period shrinks, the observation and required recharge durations required will be scaled down as well.

Orbit Operations

After the ~200 aerobraking passes complete and the spacecraft is in its stable, 1500 km, 85° inclination orbit, the instrument teams will be in prime position for making new discoveries and answering long-held questions about this dynamic world.

For this Circular Orbit Phase, three types of science campaigns have been devised. Each of these campaigns, or instrument combinations, was formulated to manage power and data

rates. The telecom system is assumed to be operational except when the spacecraft is occulted from Earth's view. Early in the phase the spacecraft is occulted from Earth about 40% of the time (occultations occur from 60°N to 60°S). When the spacecraft is not occulted, it will downlink; Radio Science data is captured during every downlink.

Titan completes one rotation and one orbit of Saturn every 16 days. For this reason, campaign durations of 16 days were chosen. During each revolution, the spacecraft will complete 80 orbits of Titan. This will allow the instruments in a campaign to view Titan from every position in the magnetosphere, and from every possible Sun and Saturn lighting angle. The operations scenarios for the Circular Orbit Phase differ significantly from those for tour flybys and aerobraking passes in that they are maintained for full orbits, in fact 80 orbits. If an instrument is not included in a campaign, it is assumed to be off or in standby.

Campaign 1: Atmosphere and Ionosphere. This campaign will include the PMS and MAPP instruments. Their observations will identify and measure ions and neutrals globally for various Sun angles. Section 4.6.4 contains more detail in modeling this campaign.

Campaign 2: Surface Map. This campaign will include the HiRIS, TiPRA, and MAPP instruments. Their observations will produce global maps in up to four colors, accomplish global altimetry and sounding with better than 10 m resolution, and perform surface spectrometry. Section 4.6.4 contains more detail in modeling this campaign.

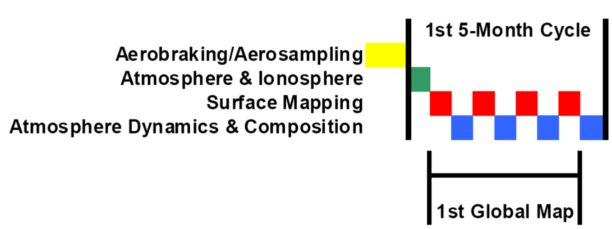
Campaign 3: Atmospheric Dynamics and Composition. This campaign will include the TIRS and SMS instruments. Their observations will measure temperatures, composition, and winds, globally. If the TIRS requirements are met as predicted, a variation of Campaign 3, with PMS taking the place of TIRS once per five month cycle is feasible. Section 4.6.4 contains more detail in modeling this campaign.

Once circular orbit is reached, Campaign 1 will execute for 16 days. During this time, the PMS and MAPP teams will attempt to determine how energy is deposited in the upper atmosphere to drive the chemistry and escape rate of major atmospheric constituents. Also, they will try to determine the processes leading to the formation of complex organics in Titan's atmosphere. During this 16 day campaign, PMS will collect ~27.6 Gb and MAPP will collect ~15 Gb of uncompressed data volume. Note: Instrument data is compressed before it is routed to the SSR.

After Campaign 1 has completed, Campaign 2 begins and will execute for the next 16 days. MAPP is still operational, but now HiRIS and TiPRA will begin to characterize the amount of liquid and the major processes transforming the surface. They will generally begin to help answer questions regarding how Titan functions as a system, and investigate similarities and differences with Earth. Also, they will try to assess to what level of complexity prebiotic chemistry has evolved. TiPRA will collect 23.7 Gb and HiRIS will collect 210 Gb of uncompressed data volume.

Campaign 3 executes for the next 16 days. For this set of 80 orbits, the TIRS and SMS instruments will quantify the escape flux of elemental nitrogen, carbon, and hydrogen, and the exospheric flux of oxygen into the atmosphere. They will also characterize the major chemical cycles and relative importance of transport. This will also contribute to understanding how Titan functions as a system. SMS will collect 19.3 Gb and TIRS will collect 13.8 Gb of uncompressed data.

After Campaign 3 completes, Campaign 2 and Campaign 3 alternate for the remainder of the first five months. **Figure 4.6-4** shows the operations scenario for the first five months of the 1500 km Circular Orbit Phase. At the end of five months, some or all of the cycle illustrated below can be repeated, depending on the progress of science goal accomplishment.



*Five-month cycle = Nine periods of 16 days.

Figure 4.6-4. *Operations scenario for first five months in Titan orbit.*

Each orbit type (campaign) would be maintained for 16 days (one Titan revolution) to enable global coverage:

- **Atmosphere and ionosphere (PMS and MAPP):** Identify and measure ions and neutrals globally for various Sun angles.
  - All of the required science data is returned and, if need be, the system has the ability to return an additional 44 Gb over the duration of this campaign.
- **Surface map (HiRIS, TiPRA, and MAPP):** Global map in up to four colors; global altimetry with better than 10 m accuracy; surface spectrometry.
  - 220 Gb of the required science data is returned during this campaign, and 27.4 Gb will remain on the SSR at the end of this campaign.
- **Atmosphere dynamics and composition (TIRS and SMS):** Measure temperatures, composition, and winds, globally.
  - All of the required science data is returned and, if need be, the system has the ability to return an additional 70 Gb over the duration of this campaign.

When modeling the SSR state (loading and unloading), the compressed data volume numbers are used because the data is compressed prior to being routed to the SSR.

Nominal Instrument Pointing

The instrument mounting locations and orientations were chosen to optimize science data collection during the Titan Orbit Phase.

While the spacecraft is in orbit, the remote sensing and sounder instruments are all pointed to nadir and the fields and particles instruments all benefit from '+Y to ram' pointing. The HGA can articulate to point to Earth. Nominally, the spacecraft will not need to articulate for the instruments to gather their data. During Campaign 3, SMS and TIRS will have mechanisms in place for scanning and limb viewing without spacecraft motion. It is convenient that any subset of the instruments (given enough power) can take data simultaneously. As science requirements are assessed and new needs arise, a variety of other campaigns (instrument combinations) can be created for consideration.

4.6.4 Data Return Strategy

When instruments are said to be "operational," it is assumed that they collect data continuously at the rates specified in **Table 4.6-7**. Data acquired by the science instruments will either be stored on the SSR or transferred directly to Earth in the downlink stream. All acquired data will be transmitted to the DSN. For each week during the mission, data volume estimates will be provided to the operations teams based on the scheduled DSN tracking for the period.

During the Saturn Tour Phase, each Enceladus flyby will accumulate ~15 Gb of uncompressed science data as the telecom system is in standby. In the hours following the flyby, telecom will go active and downlink the data to a 34 m DSN antenna. Taking data compression into account, and assuming a conservative downlink rate of 140 kbps, the Enceladus flyby data should all be on the ground in 6.5 hours. There is also the "Radio Science Option" for an Enceladus flyby in which the telecom system is operational throughout. The Radio Science data is collected at the DSN station and is not recorded on the SSR with the other science data. This option records about 15 Gb of data that will be played back during and after the flyby. For Titan flybys, ~26 Gb of uncompressed data will be collected in the 20 hours around closest approach; it will be compressed and routed to the SSR. Two 7 hour

***Table 4.6-7.** Circular Orbit Phase data volume calculations.*

		Data Rate (Mb/s)	Compressed Rate (Mb/s)	Operating Time (min) per Orbit	Uncompressed Data Volume (Mb) per Orbit	Uncompressed Data Volume (Mb) per 16-day Campaign
Campaign 1	PMS	0.020	0.020	287	344	27.5
	MAPP	0.010	0.010	287	172	13.8
Campaign 2	HiRIS Imager	0.300	0.077	115	2070	165.6
	HiRIS Spectrometer	0.080	0.080	115	552	44.2
	TiPRA Altimeter	0.030	0.030	115	207	16.6
	TiPRA Sounder	0.300	0.300	5	90	7.2
	MAPP	0.010	0.010	287	172	13.8
Campaign 3	SMS	0.014	0.007	287	241	19.3
	TIRS	0.010	0.005	287	172	13.8

downlink periods will follow each flyby, during which all of the Titan flyby data will be received at the DSN. The orbiter will collect a total of 521 Gb (uncompressed) during the Saturn Tour Phase (see **Table 4.6-8**).

In §4.6.3.2, two different data acquisition scenarios were presented for the Aerobraking Phase. The aerobraking orbit periods range from 20 hours down to ~4.8 hours. For the first several aerobraking orbits, with period >13 hours, Scenario A1 collects a total of 10.8 Gb of science data per orbit. The HiRIS data, which is ~90% of the total data volume, is compressed by a factor of four for downlink. With telecom on continuously during these orbits, the data obtained on each orbit will be returned on that same orbit. As the aerobraking orbits become shorter, and less data is acquired per orbit, the record and downlink rates will continue to be comparable. For this reason, all science data gathered during aerobraking will be received at the DSN shortly after it is acquired.

For the A2-type aerobraking scenario, 7.0 Gb of data will be collected per orbit. Again, this aerobraking science data will be received on the ground shortly after it is acquired. The orbiter will collect a total of 1030 Gb (uncompressed) during the Aerobraking phase (see **FO-5**).

Once aerobraking is complete and the mission begins orbital science campaigns, the data return strategy is more dynamic. Campaign 1 (Atmosphere and Ionosphere) has 550 Mb of playback margin per orbit. Over the course of its 16 days, this campaign can unload 44 Gb from the SSR if need be. **Figure 4.6-5** shows the SSR state throughout one Campaign 1 orbit.

Campaign 2 (Surface Mapping) records 341 Mb more than it can play back per orbit. Over the course of its 16 days, this campaign will leave 27.4 Gb of compressed data on the SSR. **Figure 4.6-6** shows the SSR state throughout one Campaign 2 orbit.

Campaign 3 (Atmosphere Dynamics and Composition) has 885 Mb of playback margin per orbit. Over the course of its 16 days, this campaign can unload 70 Gb from the SSR if need be. **Figure 4.6-7** shows the SSR state throughout one Campaign 3 orbit.

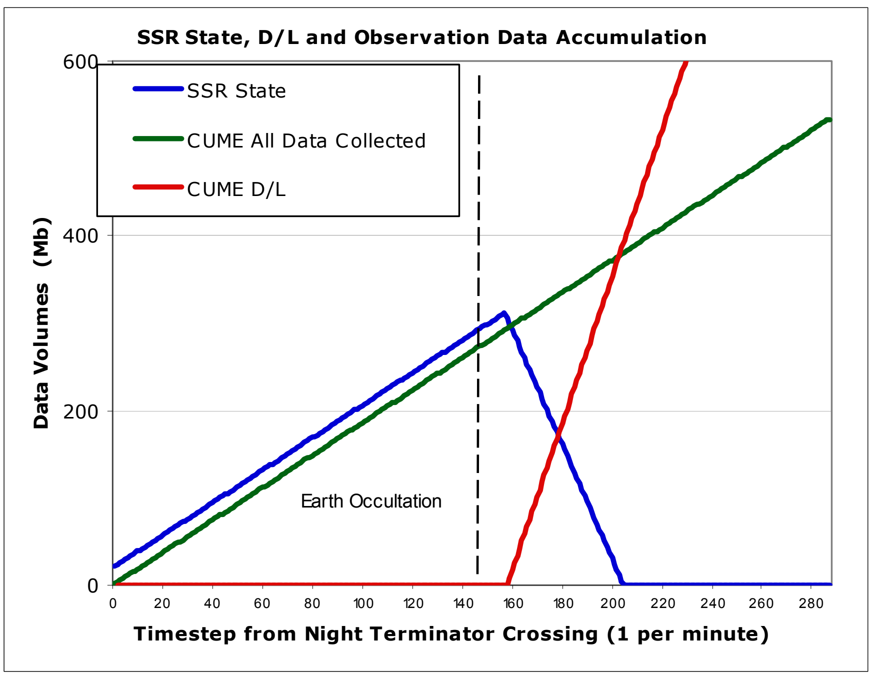


***Figure 4.6-5.** SSR state through a single orbit of Campaign 1. The cumulative record and playback are also plotted for the 287 min orbit. In this scenario, much more data can be played back than has been recorded. The vertical dashed line represents the day terminator, the spacecraft coming into the daylight, and where downlink may begin.*

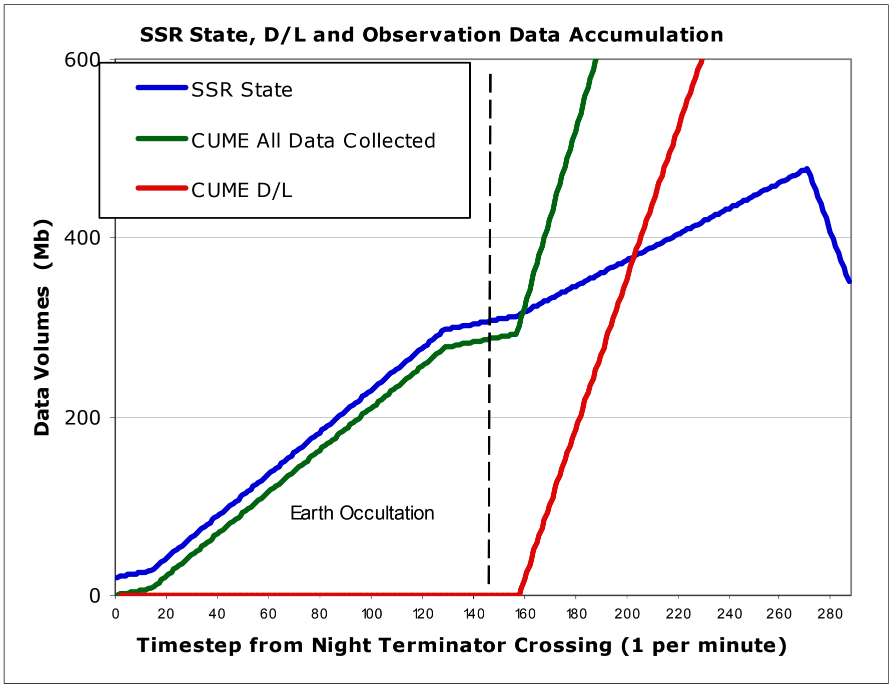


Figure 4.6-6. SSR state through a single orbit of Campaign 2. The data recorded exceeds the downlink capacity. The SSR gets cleared during the next campaign.

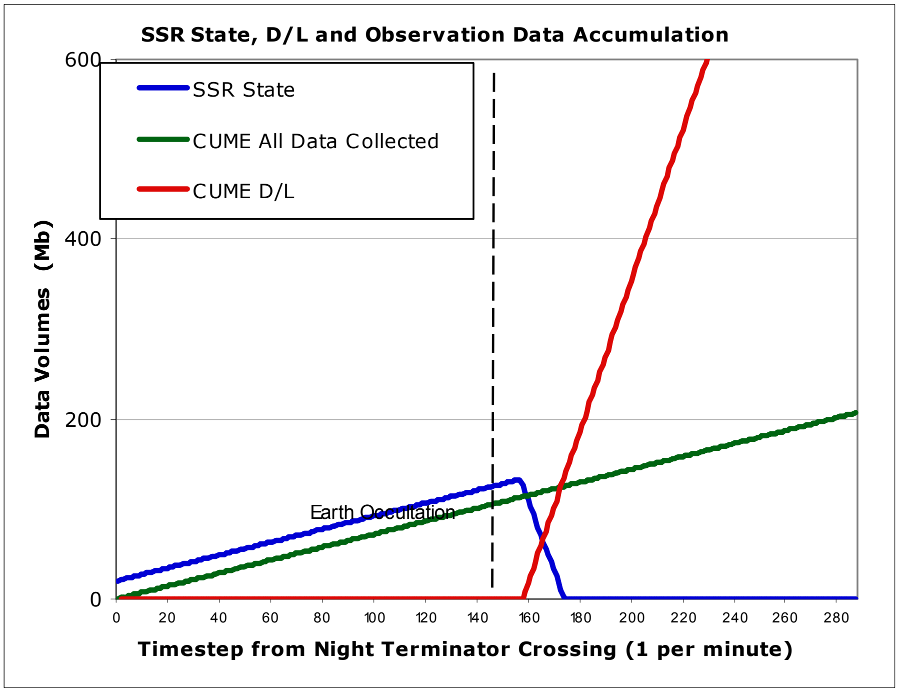


Figure 4.6-7. SSR state through a single orbit of Campaign 3.

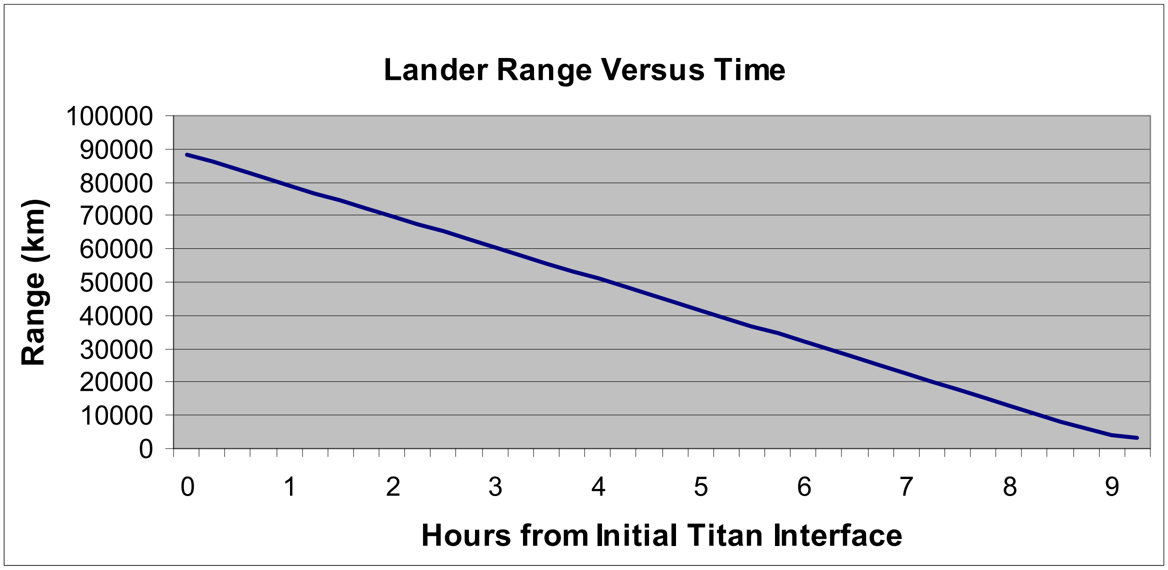


Figure 4.6-8. *Lander to orbiter range during 2nd Titan flyby.*

The operations scenario for the Titan Orbit Phase alternates Campaign 2 and 3 for several cycles. This not only works well when considering science data acquisition, but this scenario is also advantageous when considering the data return strategy.

The HiRIS imager has the capability to acquire two or more bands/colors simultaneously. Hence the HiRIS data rate could potentially double (from 300 kbps to 600 kbps). This would leave the SSR completely full (32 Gb) after each campaign 2 sequence. Another option would be to increase the Spectrometer data rate. In either case, Campaign 2 will be followed by one of the other campaigns (typically Campaign 3) in order to return all of SSR data. **Table 4.6-7** shows how the data volume for each orbital campaign was calculated. The orbiter will collect a total of 3300 Gb (uncompressed) during the Circular Orbit Phase.

In Situ Data Capture

During the lander's nine hour mission, it will acquire and send data continuously to the orbiter at rates ranging from 2 to 1024 kbps. The lander to orbiter data rates and range as a function of time are shown in **FO-5** and **Figure 4.6-8**, respectively. The initial communications data link will occur when the orbiter-to-lander range is 87,000 km. This range will decrease by ~10,000 km each hour over the next eight hours, and the data rate increases significantly after the first few hours. The onboard storage capacity for the lander far exceeds what will be required to hold the highly-valued lander data. The link to the orbiter will allow the full transfer of this data multiple times. This lander to orbiter link can support the transfer of up to 3.42 Gb that will be stored on the orbiter's SSR, and then played back to Earth multiple times to ensure its safe return. The geometry of the lander release and orbiter communication throughout the lander mission is shown in **FO-1**.

The montgolfière to orbiter data rates and range as a function of time are shown in **FO-5** and **Figure 4.6-9**, respectively. During the montgolfière's six month prime mission, the montgolfière to orbiter link can support the transfer of up to 1.3 Tb to the orbiter. For the majority of the Saturn Tour Phase, the orbiter to montgolfière distance will be between 1 and 3 million km, and often this distance will be less than 1 million km. Plots showing the montgolfière visibility and data flow are shown in **FO-5**. The "montgolfière in view" plot gives approximate times for the view periods. In practice, the montgolfière will scan for the orbiter beacon, and the link will be established before data flow begins.

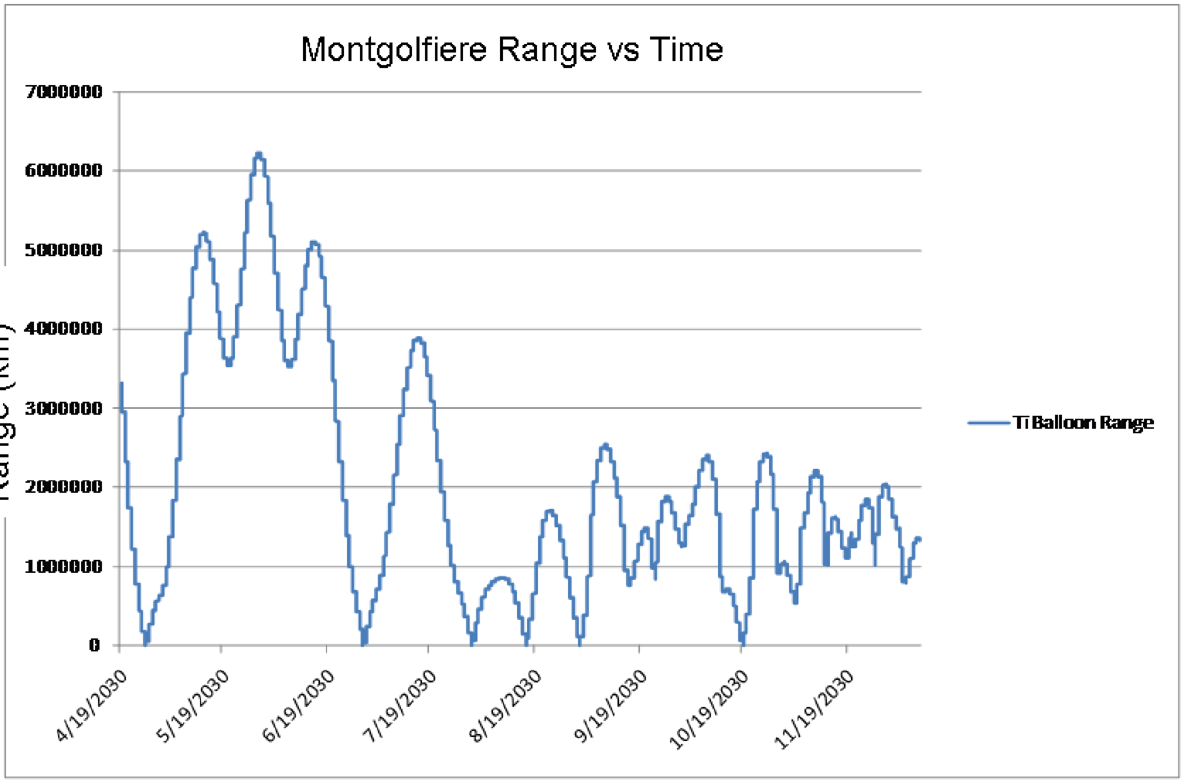


***Figure 4.6-9.** Montgolfière-to-orbiter range during the 6-month montgolfière prime mission.*

To summarize, there are seven extended periods (ranging from three days to two weeks) during the montgolfière's six month prime mission in which the range is less than 1 million km and the montgolfière is in view. It is during these seven periods that the rate significantly increases and exceeds 1 Mbps. Correlating the montgolfière plots in **FO-5** and **Figure 4.6-9**, one can see how the range and view periods will lead to the seven high data rate periods, and in turn the seven large jumps in the montgolfière data volume return. This data link capability far exceeds the montgolfière science data return requirement.

4.6.5 Data Processing and Science Planning

The sequence development process is likely to be straight-forward, especially during the Titan Orbit Phase. The instrument mounting locations, orientations, and fields of view were selected to optimize data collection during this phase. The remote sensing and sounder instruments are all aligned and will be nominally nadir pointed, while PMS and the MAPP instruments all benefit from the '+Y to ram' attitude. Nominally, the spacecraft will not need to articulate for the instruments to gather their data. SMS and TIRS will have mechanisms in place for scanning and limb viewing without changing the spacecraft's nominal attitude. Therefore, there should be no need for spacecraft pointing negotiations. This will reduce ground operations complexity, and in turn, cost. The Mission Operations System (MOS) is described in §4.5.1.2.

The three orbital campaigns described in §4.6.3.2 can be directly transferred into 16 day sequences. When developing a sequence, the operations teams will know by the campaign (or sequence) number which instruments are operating in the sequence and which are not. A 16 day development process is anticipated for each 16 day sequence execution. Only the MAPP instruments operate in back-to-back sequences, so generally speaking, once one sequence has been developed and uplinked, an instrument team will begin developing instrument commands for their next operation period which is 16 days away. This has the added benefit of having the majority of instrument teams involved in only one sequence development process at one time. **Figure 4.6-10**

Develop Campaign 1	**Campaign 1 Execution**			
	Develop Campaign 2	**Campaign 2 Execution**	Develop Campaign 2	**Campaign 1 Execution**
		Develop Campaign 3	**Campaign 3 Execution**	Develop Campaign 3

Figure 4.6-10. *Ongoing sequence execution and development during orbit phase.*

illustrates this simple sequence development schedule.

It is convenient that any subset of the instruments (given enough power) can take data simultaneously. As science requirements are assessed and new needs arise, a variety of other campaigns (instrument combinations) can be created for consideration.

Sequence development during the Saturn Tour Phase will include the integration of activities around the Titan and Enceladus flybys, as well as the capture and relay of the *in situ* data.

The sequence that covers the first Titan flyby will be dedicated to tracking and receiving data from the montgolfière. For the three-day period from the initial orbiter to montgolfière interface to the time the orbiter crosses Titan's horizon, the focus of this sequence will be the safe capture and relay of the montgolfière data.

The sequence that includes the second Titan flyby will be dedicated to the commanding necessary to release, track, and capture the data from the lander. This momentous data will be recorded onboard the orbiter and played back to Earth numerous times over multiple DSN stations to ensure its safe return.

The montgolfière prime mission duration is scheduled for six months. The montgolfière-to-orbiter data rate is a function of range and view period, and these rates are substantial whenever the orbiter is within 1 million km (and in view) of the montgolfière (see **Figure 4.6-9** and **FO-5**). This link will be able to support the return of all of the montgolfière data, while the orbiter instruments make their own measurements of Titan during the five Titan encounters that remain before the end of the montgolfière prime mission. The first Enceladus encounter does not occur until after the montgolfière prime mission has completed.

With sequences dedicated to the montgolfière and lander for the first two Titan passes, and the significant montgolfière-to-orbiter data link, the majority of the activities involving the three vehicles will be mutually exclusive.

It is recognized that the life of the montgolfière may well extend into the Circular Orbit Phase of the mission; there is excess capacity in the planned orbital campaigns that can support montgolfière extended mission data relay.

4.6.6 Mission Performance

The Science Accomplishment Timeline for the mission is shown in **Table 2.4-4**. It gives the timeframe for the collection of the data sets that will meet each of the science goals and objectives throughout the mission. The science operations scenarios detailed in §4.6.3 drove the timeline for the accomplishment of the science objectives.

Table 4.6-8 shows the data volume accumulations for the orbiter, lander, and montgolfière through the Saturn Tour Phase. The montgolfière's six-month prime mission will come to an end in October 2030 near the time of the sixth Titan flyby.

Global Mapping

Figure 4.6-11 and **Figure 4.6-12** show the ground tracks for 16 consecutive orbits (20% of a campaign) and the solar phase angle. The solar phase will vary throughout the mission as the orbit plane rotates as described in §4.3.8. The HiRIS imager maps 25% of Titan's surface in a single band (color) with every Campaign 2. Four of these campaigns will provide coverage of 80% of the surface with the desired 5–10% overlap.

The average data volume per Earth day is shown for each instrument in **Figure 4.6-13** for the Circular Orbit Phase. A summary of the total data acquisition for the entire mission can be found in **FO-5**.

Table 4.6-8. Cumulative data volume during Saturn Tour Phase shown at flyby milestones.

Flyby	Time	Orbiter Data Volume (Gb)	Balloon Data Volume (Gb)	Lander Data Volume (Gb)	Total Data Volume (Gb)
Ti1	April 26, 2030	26	146	0.0	172
Ti2	June 29, 2030	52	226	3.4	281
Ti3	July 31, 2030	78	416	3.4	497
Ti4	August 16, 2030	104	764	3.4	871
Ti5	September 1, 2030	130	1020	3.4	1153
Ti6	September 17, 2030	156	1200	3.4	1359
Ti7	October 18, 2030	182	1310	3.4	1495
Ti8	November 3, 2030	208	1310	3.4	1521
En1	November 7, 2030	223	1310	3.4	1536
En2	November 14, 2030	238	1310	3.4	1551
En3	November 21, 2030	253	1310	3.4	1566
En4	November 28, 2030	268	1310	3.4	1581
En5	December 5, 2030	283	1310	3.4	1596
En6	December 11, 2030	298	1310	3.4	1611
En7	December 18, 2030	313	1310	3.4	1626
Ti9	December 21, 2030	339	1310	3.4	1652
Ti10	January 6, 2031	365	1310	3.4	1678
Ti11	February 7, 2031	391	1310	3.4	1704
Ti12	February 23, 2031	417	1310	3.4	1730
Ti13	March 27, 2031	443	1310	3.4	1756
Ti14	June 29, 2031	469	1310	3.4	1782
Ti15	July 28, 2031	495	1310	3.4	1808
Ti16	August 31, 2031	521	1310	3.4	1834

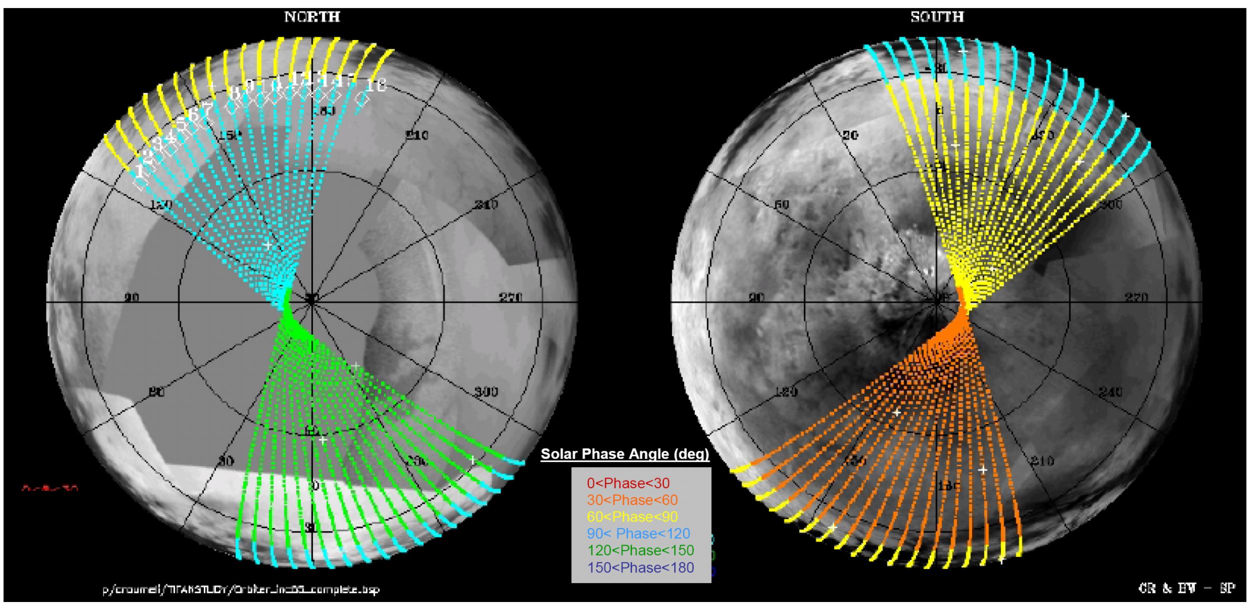


Figure 4.6-11. A polar view of the ground tracks for 16 consecutive Titan orbits (20% of a campaign). Solar phase angle is also shown throughout each orbit. (Courtesy of C. Roumeliotis and B. Wallis.)

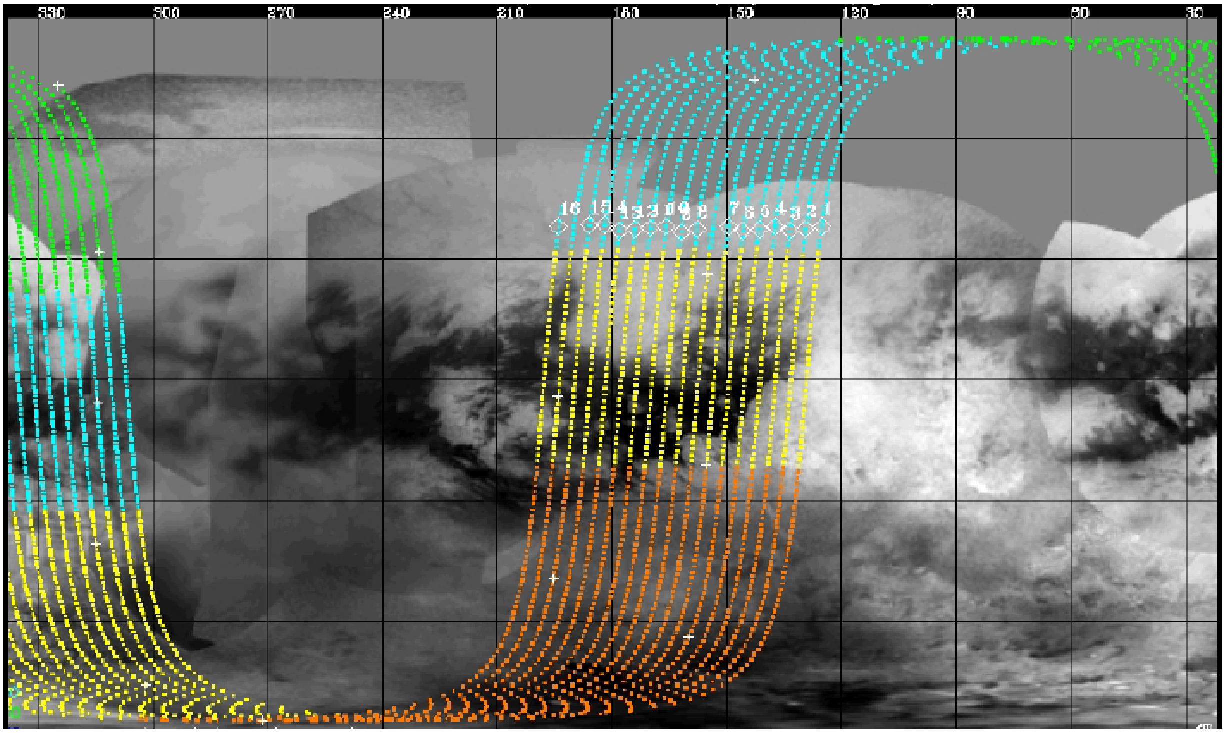


__Figure 4.6-12.__ A cylindrical view of the ground tracks for 16 consecutive Titan orbits (20% of a campaign). Solar phase angle is also shown throughout each orbit. (Courtesy of C. Roumeliotis and B. Wallis.)

Campaign 1
Atmosphere and Ionosphere
(Data per Earth day [Mb])

PMS	1830
MAPP Magnetometer	274
MAPP Energetic Particles	456
MAPP Langmuir Probe	10.7
MAPP Plasma	107
RSA	Received at DSN

Campaign 2
Surface Mapping
(Data per Earth day [Mb])

HiRIS Imager	10,350
Spectrometer	2760
TiPRA	577
MAPP Magnetometer	274
MAPP Energetic Particles	456
MAPP Langmuir Probe	10.7
MAPP Plasma	107
RSA	Received at DSN

Campaign 3
Atmospheric Dynamics and Composition
(Data per Earth day [Mb])

SMS	1277
TIRS	912
RSA	Received at DSN

__Figure 4.6-13.__ Data volume (uncompressed) per instrument per Earth day for Circular Orbit Phase.

4.7 Planetary Protection

4.7.1 Overview of Planetary Protection

Planetary protection (PP) requirements for Titan are in a period of revision, following the significant discoveries from the Cassini-Huygens mission. The final fate of the TSSM orbiter, impacting on the surface, means that the mission would likely be classified as category II under current COSPAR and NASA policy (COSPAR 2002, NASA 2005), with comparatively few requirements. However, the study team recognizes that the NASA Planetary Protection Officer has received advice from the Planetary Protection Subcommittee of the NAC to protect Titan at a higher level (equivalent to COSPAR category III). In addition, it is anticipated that COSPAR will review planetary protection status for icy moons in the near future, potentially before the end of phase A and the formal TSSM mission planetary protection categorization request.

In consequence, the approach to planetary protection compliance for the TSSM mission concept can be summarized as follows:

Accepting that the scientific case justifies it, and that the NASA PPO will likely require it, the study will manage planetary protection for the proposed mission to the COSPAR category III level. This will be achieved through:

- Managing the descent to the surface, using resources such as propellant retained for the purpose, such that the probability that the spacecraft will contaminate any liquid water body on Titan does not exceed 1×10^{-4}.
- Ensuring that contaminated spacecraft hardware is not co-located with a perennial heat source capable of creating liquid water on the surface or in the shallow sub-surface (i.e., an RTG or components thereof. The viability of this approach is based on previous data for Mars. Confirmatory analysis will be performed in Phase A).

The NASA Planetary Protection Officer has indicated support for this approach, given that specific requirements and constraints for Titan and the broader Saturnian system are met (Conley 2008).

4.7.2 PP Requirements

Current PP policy (NPR 8020.12C, NASA 2005) identifies Titan as a category II target. On this basis, only documentation of the mission implementation is required for both orbiter and lander missions.

However, the policy states that:

Planetary protection requirements for each planned mission will be determined by the NASA PPO, in accordance with this document, and consistent with the policy and guidelines of the Committee on Space Research (COSPAR), recommendations of the Space Studies Board of the National Research Council (NRC), and advice from the NASA Advisory Council.

The TSSM study team has the objective of meeting anticipated requirements, based on the known current best advice to the NASA PPO.

The principal advice is to avoid, at the 1×10^{-4} probability level, the “inadvertent contamination of a liquid water body.”

In addition, it is anticipated that there will be requirements to avoid harmful contamination (by unintended impact) of any other of the Saturnian satellites. The baseline is the approach for Cassini, where the requirement is to avoid inadvertent impact at the 1×10^{-3} probability level per object for the whole mission.

4.7.3 PP Technical Approach

It has been discussed with the NASA Planetary Protection Officer that a spacecraft that does not create an environment conducive to the replication of terrestrial biology would meet the intent of the current advice, and would therefore be in compliance. The guidance received for the time period for which this analysis is required to apply is 1000 years.

The key criterion is that the spacecraft will not cause viable terrestrial organisms to be placed in an environment with T>-80°C (>193K)—a conservative implementation of one of the so-called “limits of life” for terrestrial biology.

TSSM proposes to meet this requirement by:

- Passive/active deorbit at end of mission, ensuring avoidance of geographic/thermal anomalies. The major features of concern are potential cryovolcanic regions, which, if any are active, may include localized bodies of aqueous liquid. If the science phase of the mission demonstrates that the active areas of these regions comprise a fraction rep-

resenting less than 0.01% of the Titan surface, then the probability of contamination requirement can be met by a passive deorbit. If however, this is uncertain, an active deorbit will be required, for which propellant has been allocated. In this case, the probability requirement will be met by a combination of the probability of an off-target impact in a cryovolcanic region based on spacecraft reliability to perform the appropriate deorbit avoidance maneuver and the occurrence of such cryovolcanic features on the surface.
- Analysis to confirm that local ASRG/MMRTG heating will not transgress the "limits of life" and/or that ASRG/MMRTGs will not co-locate with contaminated hardware. In the first case, it is expected, based on parallel Martian analyses, that perennial heat sources such as ASRGs and MMRTGs do not form liquid water in Titan ambient conditions after impact; it is expected to be too cold. However this will have to be demonstrated for a series of case scenarios (buried versus exposed, different surface chemical compositions, accounting for seasonal variations in ambient conditions), which is outside of the scope of this study. Models to do these analyses exist at JPL and these will be employed to generate an early analysis output during Phase A.
- In the case where the analysis does not guarantee that the "limits of life" will not be transgressed, the project will demonstrate, potentially with minor design modifications, that entry through the Titan atmosphere always results in spacecraft break-up such that contaminated hardware and perennial heat sources are never co-located on the surface.

Note that planetary protection implementation issues for any ESA *in situ* elements (as described in §4.4.5) are not addressed in this study; this would be an ESA responsibility. However, accommodation is made in the costing analysis for planetary protection interface management and handling during launch operations.

As was done for the Cassini extended mission, tour trajectories will be designed to avoid collision with Titan or Enceladus that would place spacecraft hardware in contact with subsurface liquid water at the appropriate probability level (the study team recognizes that this may be a more stringent requirement than for the other Saturnian moons).

4.7.4 Missions Operations

Data from the operational phase of the mission, particularly during the Titan Orbital Phase, will inform the true environment to be experienced by the hardware following the end of the mission. It is expected that the NASA PPO may review constraints on the mission based on the spacecraft's ability to meet the requirements described in §4.7.2.

4.8 Selected Activities for Phase A Study

There are several open issues and trades that were outside the scope of this year's study but that are being tracked for future Pre-Phase A and Phase A work. Typical activities for Pre-Phase A and Phase A assessment include:
- Further refinement of the SEP stage configuration.
- Evaluate need for engine cover
- Thruster plume impingement analysis
- Fault containment design and redundancy trades
- Monitor ASRG development
- Monitor NEXT thruster development
- Monitor UST development
- Perform detailed spacecraft vibration analysis for ASRGs
- Alternative configuration trades
- Revisit main engine redundancy strategy and 1 versus 2 main engine trade
- Perform detailed end-to-end planetary protection analysis, including analysis of end of mission disposal scenario
- Optimize memory sizing for computing, instrument sequences, parameters, etc.
- Consider instrument processing, data compression needs by C&DH
- Consider dedicated payload processor shared across instruments
- Pointing control and timing analysis for selected instrument payload
- Evaluate ballast/balance needs
- Perform ACS dynamic analysis
- Evaluate main engine restart constraints during critical events
- Evaluate fault tolerance of engine gimbals

- Optimize placement of MGA
- Optimize placement of LGAs and determine coverage post-launch
- Flight software architecture trades including operability
- C&DH hot/warm/cold back-up strategy
- Refine RCS propellant sizing
- Refine aerobraking design
- Refine *in situ* element accommodation with ESA partners
- Evaluate component lifetime issues
- Refine instrument layout and optimize placement of radiators and spacecraft orientations
- Evaluate Model Based Engineering for use in the mission operations phase
- Further optimize mission design for purposes of the instrument AO

4.9 Technology Assessment

The TSSM study team focused on design solutions that would not require new technology to achieve the Level 1 Science requirements. NASA's Evolutionary Xenon Thruster (NEXT) and the Advanced Stirling Radioisotope Generator (ASRG) are two enhancing technologies in advanced stages of engineering development that were adopted to add robustness to the mission architecture. In the case of each of these, there is a "fallback" to flight-qualified alternatives if the baseline option does not realize its promise in time for this Outer Planet Flagship Mission. In the final analysis, the Titan Saturn System Mission could be accomplished with or without these new developments, but the mission will be more robust and more capable with them.

Finally, the selection of the Universal Space Transponder (UST) for the radio takes advantage of ongoing developments in deep space communication techniques that are intended to replace the SDST. These activities are funded by SOMB, Space Communications Technology Program and JPL investments to produce EM hardware, firmware, software, and documentation by 2012. The project cost estimate includes $10M for flight qualification for TSSM. In the case where the development does not deliver USTs on the project schedule TSSM can fall back to the current SDST, Electra proximity link and Ka-band translator with minor mass and power impacts that can be accommodated within the current resources.

ASRG

The ASRG, with its high specific power and low ^{238}Pu usage has many advantages. The higher specific power (power-to-mass ratio) and lower ^{238}Pu requirement relative to the MMRTG alternative reduce both the cost and mass of the power system. This improved performance and efficiency is illustrated in **Figure 4.9-1**. Furthermore, TSSM would be a significant step for NASA in its deployment of advanced radioisotope power systems while simultaneously freeing up existing ^{238}Pu supplies for other critical missions. There are specific advantages for this mission as well. The end-of-life power budget of the Baseline mission allows for the complete failure of 1 ASRG with no impact to the mission, for example. Finally, the mass and cost margins carried by TSSM allow the mission to fall back to the MMRTG without impact to the Baseline mission science.

While the ASRG offers the advantages described above, the Baseline mission does allow for full mission success through the use of the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). All mission objectives will still be achieved as described in §4.1.1. The MMRTG offers the obvious advantage that it has already gone through its development stage and will be launched on the Mars Science Laboratory (MSL) in 2009. The study team recognizes that an assessment must be made in Phase A to determine the availability of the ASRG and that this decision will involve guidance from and participation with the Science Mission Directorate. **Figure 4.9-2** shows the current notional use of the ASRG and MMRTG. This is preliminary, but indicates one and perhaps two ASRG missions prior to the Baseline TSSM launch date in 2020.

Based on technical trades, the study team has chosen the ASRG as the baseline power source, in line with NASA's vision for the future of deep-space power systems. The team believes that TSSM is an excellent application to capitalize on the efficiency of ^{238}Pu usage. It will demonstrate the impact of the ASRG on long-term planning for missions that require radioisotope power systems. However, the team, when considering the implementation of

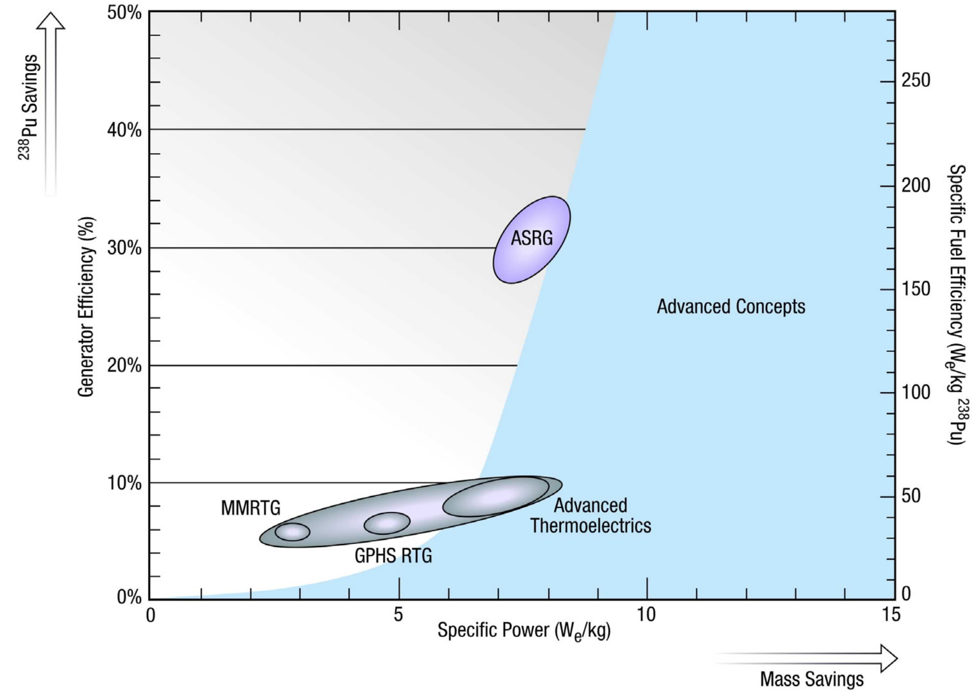


Figure 4.9-1. *The ASRG improves on ^{238}PU use and specific power at the same time.*

Flagship / New Frontiers / Discovery/Scout / Mars / Lunar / Other	Projected Launch Year	Power Req'm (W_e)	RPS Type	^{238}Pu Usage (kg)	
Mars Science Lab	2009	100	1 MMRTG	3.5	In Development
Juno (New Frontiers 2)	2011	No RPS Requirement			In Development
Intl Lunar Network	2013	25-50	Small RPS	0.44	Under Study
Discovery 12 / Scout	2014	250	2 ASRG	1.8	Under Study
New Frontiers 3	2016	Directed Non-RPS		RHU?	
Mars 2016	2016	150-300	1-2 ASRG	24.5	
Discovery 13	2017	No RPS Option		RHU?	
Outer Planets Flagship 1	2018-2022	600-850	5-7 MMRTG or ASRG	4.5-24.5	Under Study
Solar Probe	2020	Directed Non-RPS			

Figure 4.9-2. *Anticipated ASRG use.*

the Titan mission, itself is neutral on the choice of power systems. Either will suffice to achieve the mission goals.

Finally, a report on *Qualification of ASRGs for Flagship Missions*, is being prepared to document a recent assessment of the steps necessary to bring the ASRG from its current level of development to the maturity necessary for application on a Flagship-class mission.

Solar Electric Propulsion

Solar Electric Propulsion (SEP) provides a significant increase in capability for the mission. The increased I_{sp} allows the orbiter to carry more mass to Saturn orbit in less time than an all-chemical mission. SEP provides flexibility and robustness in the mission design should the flight elements increase in mass. If the launch mass increases past the mass mar-

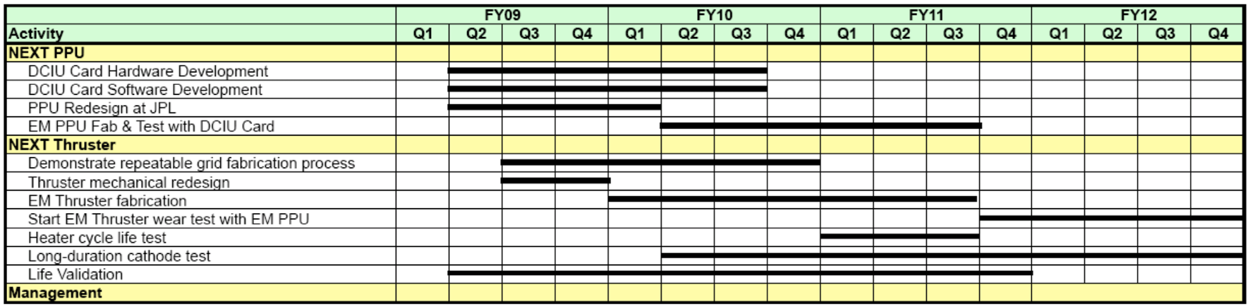


Figure 4.9-3. *NEXT development schedule.*

gined allocation, the trip time can be extended and the full complement of orbital and *in situ* elements can still be delivered to their target. The TSSM Baseline, including SEP using the NEXT ion propulsion system, represents the best science return-versus-cost solution. See §3.2 for a description of this trade.

Once development is complete, the NEXT Ion Propulsion Subsystem (IPS) will be the highest performing option among ion engines and will continue to feed forward NASA's ongoing investment in in-space propulsion, including the Digital Control and Interface Unit (DCIU) and Power Processing Unit (PPU) both integral elements of the IPS.

NEXT builds on the success of the NSTAR ion propulsion system currently operating on the Dawn mission. NEXT's increased performance puts TSSM on the fastest trajectory discovered so far by the Mission Design team. **Figure 4.9-3** shows the development timeline expected for NEXT past the current year's efforts.

If, however, NEXT does not mature at a rate that allows it to be inserted for TSSM there are other trajectories that could make use of existing flight-qualified electric propulsion systems. These trajectories would result in slightly longer trip times to Saturn. Aerojet's Hall effect thruster, the BPT-4000, has been evaluated by the team and confirmed to be a viable backup option for NEXT.

As described in §4.10, *Risk Assessment*, baselining the NEXT system carries the risk of increased cost of final development associated with using this new thruster. The TSSM Baseline cost includes 50% cost reserve on the SEP Ion Propulsion Subsystem and ample schedule contingency on the entire SEP System to address and mitigate this risk if realized.

TSSM team members have been integral in the development of the NEXT system with Glenn Research Center. Appendix H is TSSM's assessment of the efforts that would be required to bring NEXT to sufficient maturity to warrant its selection during Phase A.

Technology Summary

From the initiation of this study, the team has focused on achieving Titan, Saturn, and Enceladus science in line with the expectations of a flagship mission and the Decadal Survey while using flight-proven methods and technologies to minimize cost and risk. The team believes that these emerging capabilities, are worthy additions to NASA's arsenal of tools for use on deep space missions.

4.10 TSSM Risk Assessment

The study team has identified a number of risks to the success of the NASA portion of TSSM. Each risk has been evaluated for likelihood and consequence on a scale from 1 to 5 and positioned on a traditional 5×5 risk matrix as shown in **Figure 4.10-1.** The scale used for risk assessment is described in **Table 4.10-1**, *Risk Table Level Definitions*, in accordance with JPL's *Qualitative Risk Assessment* standards as called for by NPR 7120.5D "NASA Program and Project Management Processes and Requirements." Mitigation plans have been developed for each risk and are included in the estimated mission cost. All of these risks will be aggressively managed regardless of the standard criticality designation they have in **Figure 4.10-1**. Subsequent sections give a brief discussion of each risk and its corresponding mitigation. The risk rating is given in the title of each subsection below as an ordered pair of consequence and likelihood associated with its abbreviation as shown on the Risk Matrix (Risk abbreviation C, L).

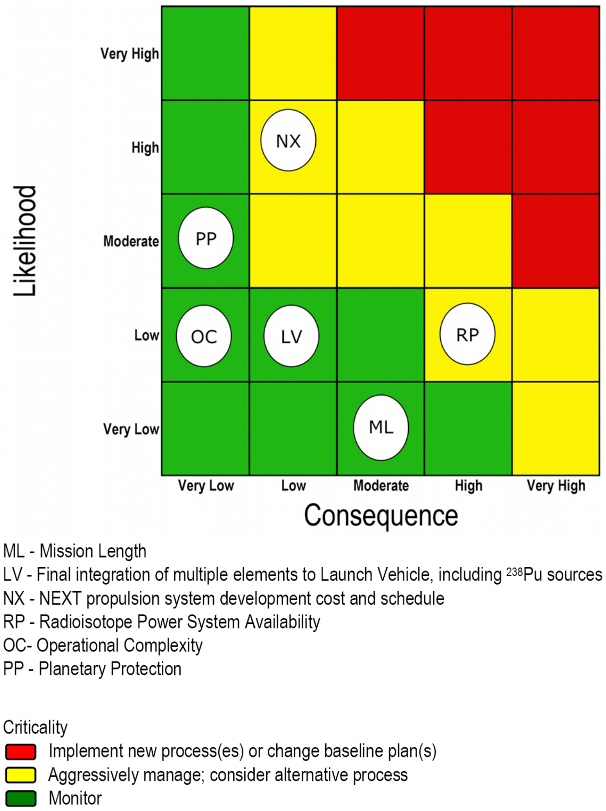


Figure 4.10-1. *TSSM risk assessment matrix.*

Management strategies for these risks including specific actions taken to address cost are discussed in §4.11.8.

4.10.1 Mission Length (ML 3,1)

Risk Statement

The duration of TSSM's primary mission, at 13 years, could lead to a moderate consequence on performance during the science-gathering phases of the mission. Missions designed to last 10–15 years in deep space require special parts and processes that fall outside the norm of the user base. Testing of electronic parts is often not extended past 5–7 years requiring extrapolation of part data beyond that period. Real-time life testing of components is problematic for systems requiring lifetimes in excess of 7 years. Based on previous successes of long life missions, the risk associated with ensuring that the design will be fully functional throughout the entire mission life time is of very low likelihood.

Mitigation

High reliability is demanded to achieve the life time requirements on the electronic, electrical and electromechanical parts of the system. Advanced parts screening, life testing and proper application of design margins required for long-lived missions such those used on as Voyager, New Horizons, Galileo, Cassini-Huygens, etc., are the basis for the design to ensure mission success.

Past missions to the outer solar system have dealt with this risk successfully. The design life for Cassini and New Horizons is only 2 years less than the projected lifetime of TSSM. Cassini is on its 1st extended mission, 11 years after launch, and will achieve a 14-year life when the extended mission is complete. Voyagers I and II continue to operate more than 30 years after launch. JPL's Flight Project Practices and Design Principles are the accumulation of many decades of experience from past long lived JPL missions. These practices and principles are applied to the entire project implementation and communicated to potential instrument and subsystem providers. All of the engineering subsystems on the orbiter and the SEP stage will be required to review and report against these practices and principles as part of their Preliminary Design Review process. The TSSM Baseline mission plan includes the cost and

Table 4.10-1. *Risk matrix definitions.*

Scale	Consequence		Likelihood
	Mission Risk	Implementation Risk	
5	Very High: Mission failure	Very high: Overrun budget and contingency, cannot meet launch with current resources	Very high: Almost certain
4	High: Significant reduction in mission return	High: Consume all contingency, budget or schedule	High: More likely than not
3	Moderate: Moderate reduction in mission return	Moderate: Significant reduction in contingency or launch slack	Moderate: Significant likelihood
2	Low: Small reduction in mission return	Low: Small reduction in contingency or launch slack	Low: Unlikely
1	Very Low: Minimal (or no) impact to mission	Very Low: Minimal reduction in contingency or launch slack	Very low: Very unlikely

effort of the rigorous parts program, life testing and verification and validation program required for such a long-lived mission to succeed.

Finally, a Knowledge capture and Management (KM) system, such as that implemented on New Horizons, is critical to ensure technical continuity among personnel from cradle to grave for long life missions. A system such as that which was developed for New Horizons will be used on TSSM.

4.10.2 Launch Vehicle Logistics and Integration of RPS (LV 2,2)

Risk Statement

The complexity of integration of multiple flight elements at the launch site coupled with the final integration of the Radioisotope Power Systems could lead to schedule delays.

Mitigation

Early planning of RPS integration and completion of the LA/NEPA process will ensure timely, successful processing at the launch site. With five ASRGs (or MMRTGs) on the orbiter and one MMRTG on the montgolfière, detailed coordination and planning will be needed with the launch vehicle provider to ensure safe and efficient installation. Because both JPL and APL have successfully completed similar efforts in the past, the likelihood of this risk occurring is judged to be low; however, each installation is configuration-dependent and requires considerable coordination with the Department of Energy (DOE), KSC, the launch vehicle provider, the TSSM project office, and the European Space Agency to avoid cost and schedule impacts. To minimize cost and schedule impacts, TSSM plans include early and detailed interface engineering with the launch site and launch vehicle provider, peer reviews of the installation plans and procedures, and Trailblazer operations that include engineering models and simulators of the RPS devices, the flight vehicles and the launch vehicle fairing.

4.10.3 NEXT Development (NX 2,4)

Risk Statement

Final-flight development of the SEP stage NEXT ion propulsion subsystem (IPS) could cost more than anticipated. Delays in development could affect the rest of the program. Switching to one of the alternative thrusters would require some redesign and additional cost.

Mitigation

As NASA continues to fund development of the NEXT IPS, the inherent risk of successfully bringing the development to a conclusion will decrease but at this time it is believe that there is a significant likelihood that completion will require allocation of cost reserve. To address this, TSSM has included a higher level of cost reserves and schedule margin than are typically required at this stage. If NEXT does not mature in time for TSSM, the Baseline mission cost and schedule reserves account for the selection of an alternative thruster which would mitigate the consequences and justifies the decision to baseline this higher performance thruster.

The NEXT thruster promises to enhance capability of TSSM as well as other deep space missions. The TSSM team fully expects NEXT to provide propulsion for many ambitious future missions to other solar system targets, while recognizing that such engineering developments have met with costly delays in the past. The project plans to work with NASA to urge a sustained effort to reduce the likelihood of these delays occurring.

Two options for an alternative thruster that meet the mission requirements have been identified to address the consequences of the NEXT thruster not being available. The BPT-4000 Hall Effect thruster available from Aerojet could substitute for the more capable NEXT system, but it would come at a marginal cost in trip time (see §5.0). It has also been shown that the commercially available XIPS thruster would also be a suitable substitute for NEXT. There is, therefore, a robust fall-back plan if the NEXT thruster does not reach flight readiness in the TSSM timeframe.

Since the NEXT thruster represents an evolution in known capability, given its predecessor on the Dawn mission (NSTAR), the TSSM team is confident that the NEXT ion propulsion subsystem will reach flight readiness on a schedule appropriate for TSSM. The perceived risk is in the cost of flight development. Taking this into account, TSSM is carrying 50% cost reserve in addition to funded schedule margin on the NEXT development and backup approaches to address this risk. As the devel-

opment progresses this risk will be aggressively managed. See §4.9.2 for more information on the NEXT development.

4.10.4 Radioisotope Power System Availability (RP 4,2)

Risk Statement

While NASA is now baselining the MMRTG for the next OPFM, it is also developing the ASRG as the long term solution to improving performance and reducing the Plutonium requirements for future planetary missions. A decision on which RPS system will be made available to TSSM is planned by NASA to occur before the start of Phase A. If that decision is delayed it will delay the system design and ultimately might have impacts on mass, power, cost and schedule. Any problems with either RPS that is selected—either in development and validation of the ASRG or in restarting the MMRTG production line—would have a high consequence on the mission since it requires a radioisotope power system.

Mitigation

The decision on the type of RPS (MMRTG or ASRG or both) for TSSM is crucial for design of the systems. The decision to use either the MMRTG or the ASRG is required in time to ensure that well-defined and stable characteristics are available to allow system designers to adequately incorporate RPS into the system. The study team will work with NASA to clearly delineate the mission requirements. However, the timing of the selection decision is not under the control of the TSSM project. The team believes that there is a low likelihood of both the delay in the decision or unanticipated problems with the selected RPS system.

Although TSSM currently baselines five ASRGs for the orbiter design (one of the five is only used as an in-flight backup), the mission can alternatively accommodate five MMRTGs with no impact to mission science as described in shown §4.4.2.9 and in Appendix E. Margins are currently being maintained to accommodate either technology. Accordingly the consequence of the RPS decision, provided it is made early, is minimal to the mission. However, the availability of either the ASRG or the MMRTG (due to late decision or issues discussed herein) represents potential risk with high consequence and is outside the control of the TSSM project.

Mitigation of these risks will require the project to work closely with the Program Executive at NASA Headquarters during the ASRG Development Program, to ensure that a final decision on RPS is made prior to the completion of Phase A and that the selected technology is capable of being flight qualified no later than Phase B with flight units available for ATLO insertion per the schedule shown in **Foldout 6**. For the montgolfière, TSSM could make use of the MSL spare MMRTG currently being held in storage.

4.10.5 Operational Complexity (OC 1,2)

Risk Statement

The complexity of operations, including multiple planetary and Saturnian-moon flybys and the support of two ESA-provided *in situ* elements could lead to an impact to operational cost.

Mitigation

The TSSM team has taken all of these factors into account and assesses this risk to be of very low likelihood and consequence. This risk is addressed in the baseline plan in a number of ways. The staffing levels applied to the operations team, the navigation team, the science planning team and the supporting engineering teams are commensurate with the levels based on the Cassini-Huygens mission experience and lessons learned. Specific differences between Cassini-Huygens and TSSM allow for some savings in Phase E. While TSSM does indeed have a 2 year tour of the Saturn System, including flybys of both Enceladus and Titan, the layout of the instrument suite and the application of a gimbaled high gain antenna allow for more efficient and cost effective science planning and operations.

The instrument suite has been laid out primarily for orbital operations at Titan. Sensors point mostly in the nadir direction, allowing concurrent scientific observations within the constraints of the power system. Rapid slews and complex changes in attitude are not required to perform multiple concurrent or serial scientific observations. Radio science, an important measurement in its own right, can be performed without disturbing the other instruments due to the aforementioned gimbaled high gain antenna. Furthermore, once the

spacecraft achieves Titan orbit the plan is to operate specific combinations of instruments in repetitive campaigns. Such regular operations are not possible with Cassini, whose every science operation is unique in geometry, timing, attitude and the instruments employed. TSSM will, on a 16 day cycle perform the same operations over and over: surface mapping and atmospheric observations follow each other, all nadir-pointed, all utilizing the pointing flexibility of the HGA to continue science observations unperturbed. Furthermore, advances in the automation of command sequencing and operational planning will be applied with full effect.

4.10.6 Planetary Protection (PP 1,3)

Risk Statement

Titan is currently a Category II target for the orbiter according to planetary protection guidelines however a Categorization level of III might be levied subsequent to this study as knowledge of cryovolcanism and access to the sub-surface grows with the continuance of the extended Cassini mission.

Mitigation

To address the moderate likelihood for an increase in Planetary Protection Categorization, the team has already assumed Planetary Protection Category III for the TSSM orbiter. The risk is fully mitigated by this approach thereby heading off the potentially moderate impact to the mission. The planetary protection approach is discussed in §4.7.

4.11 Programmatics

The TSSM programmatic approach is structured to enable effective management and decision-making.

Project management will draw from the experience in the successful design and implementation of long-life, deep-space missions such as Voyager, Galileo, Cassini, and New Horizons. Galileo and Cassini are especially relevant to TSSM development as they both involved major inter-center and international collaboration in multi-element mission implementation and instrumentation. The management approach outlined here addresses the collaborative program and includes the cost for the NASA element of the mission as well as management, system engineering and science interfaces to accommodate ESA-provided *in situ* elements similar to that which was done successfully on Cassini-Huygens, For this estimate, it is assumed that all instruments are procured outright and none would be contributed from foreign entities. As the mission evolves, this is likely to change as described in Appendix G, International Context.

4.11.1 Management Approach

The complex nature of Flagship missions calls for a cohesive partnership between the entities making up the project. TSSM's management approach draws upon extensive partnership experience and lessons learned from Galileo and Cassini-Huygens and is compliant with NPR 7120.5D. The project plan is based on a tightly integrated NASA/ESA partnership similar to the approach used on Cassini-Huygens.

The project approach includes a Work Breakdown Structure (WBS), technical management processes conducted by veteran systems engineers, and integrated schedule/cost/risk planning and management. The project would take advantage of existing infrastructure for planning, acquisition, compliance with the National Environmental Policy Act (NEPA), compliance with export control regulations, including International Traffic in Arms Regulations (ITAR), independent technical authority (as called for in NPR 7120.5D), mission assurance, ISO 9001 compliance, and earned value management (EVM).

TSSM employs JPL's integrated Project Controls solutions to manage and control costs. Skilled business and project control professionals would be assigned to TSSM, utilizing state of the art tools and executing processes that support the project cost, schedule and risk management requirements. Key attributes of the Project Controls solution are:

- The Business Manager, project focal point on all business management issues, and the project control staff lead project planners and managers in application of the most effective and efficient implementation of project control processes.
- Mature and successfully demonstrated cost and schedule tools are employed.
- Cost and schedule data are tied directly to work scope.
- 'Early warning' metrics are provided monthly to key decision makers. Metrics

include 1) cost and schedule variances based on the cost value of Work Performed and 2) critical path and slack analysis derived from fully integrated end to end network schedules. Each end item deliverable is scheduled with slack to a fixed receivable. Erosion of this slack value is tracked weekly and reported monthly.

- Integrated business management approach is applied to all system and instrument providers which includes relative performance measurement data integrated into total project database for a comprehensive understanding of project cost and schedule dynamics. Risk management processes are integrated with the Liens Management process to provide full knowledge of Project reserve status. Early risk identification is maintained to head off potential threats to project reserves. Reserve utilization decisions are made with the knowledge of risks and risk mitigation, project performance issues and increases in scope.

Requirements for project controls evolve throughout the project life cycle. Pre-Phase A and Phase A will require less support than Phases B, C, and D. During Phase B, the project controls capability is established at full strength to establish all the appropriate databases and gate products required for a successful Confirmation Review. During Phase C and D, the project controls will be fully functioning with recurring performance measurement analysis and cost and schedule tracking reports. During Phases E and F, the Project Controls function reduces to minimal levels.

4.11.2 Organization and Decision Making

The TSSM project will be led by a Project Manager (PM), who is responsible for all aspects of project development and operations. Deputy Project Managers will be chosen from any external organizations that are delivering significant elements of the mission. The PM would report directly to NASA HQ and to the JPL Director. A representative organizational chart is shown in **Figure 4.11-1**. A Deputy Project Manager is planned to support the TSSM PM with the full scope and oversight of the mission. An ESA-appointed Project Manager responsible for the *in situ* elements would have a close coordination relationship with the TSSM PM as shown by the dotted line in **Figure 4.11-1**. A TSSM Project Scientist (PS) and ESA *In Situ* Project Scientist would be appointed to represent science interests. The Project Scientist would be supported by a Science System Engineer, the Project Science Steering Group and the science planning team for the duration of the mission. A Project System Engineer (PSE) is planned at full-time for the duration of the project. A Deputy Project System Engineer is planned to support the PSE.

A Project Science Coordination Group (PSCG) would be formed with membership that includes the TSSM Project Scientist, ESA Project Scientist, and NASA Program Scientist. The PSCG would meet on a quarterly basis to coordinate on all science matters.

A Project Advisory Board (PAB) would be formed with membership that includes NASA and ESA Program Executives, TSSM Project Manager, ESA Project Manager, NASA and ESA Program Scientists and Senior Management responsible for major contributions. The PAB would meet on a quarterly basis to assess the state of the project, head off problems and knock down barriers.

Organization and day-to-day operation of the team is structured to maintain tight coordination between programmatic and technical elements of the NASA/ESA project. Monthly management planning, coordination, review and status meetings are planned using face-to-face and electronic media interactions. The project system engineering team includes members from each major contributor with and will maintain technical coordination through weekly technical interchange meetings, reviews, technical documentation, focused working groups and change control. ESA project engineers will be included in the weekly JPL project system engineering team meetings to coordinate on interfaces and accommodation details.

Decisions would be made at the lowest level possible while ensuring that a decision made in one system neither adversely affects another nor impacts the science data return. Pursuant to NPR 7120.5D, the project would include a project-level "Communications Plan" in its list of planning documents, which would include the dissenting opinion process. This detailed plan for communication and

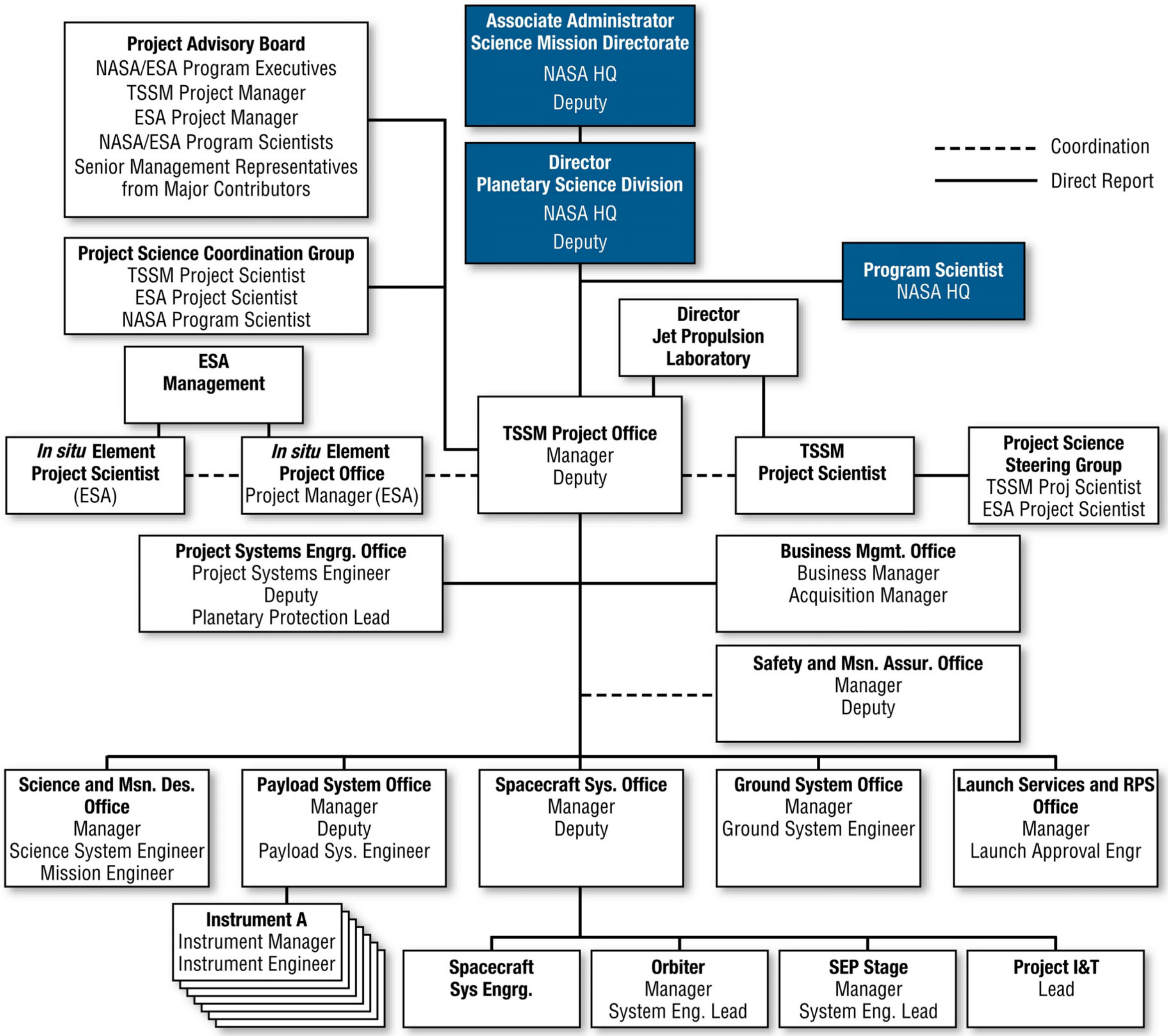


Figure 4.11-1. *The TSSM organization builds upon and applies the Cassini-Huygens experience to enable efficient management and decision making for an effective NASA/ESA collaboration.*

decision-making will be completed in Phase A. The PM is the final project authority for all decisions that cannot be resolved at lower levels. The Project Scientist will have a prominent role in arbitrating science priorities in support of science planning for the mission. For decisions involving the quality and quantity of science data deliverables, the Project Scientist will provide concurrence.

Replacement of the JPL PM and Project Scientist will be made only with concurrence by NASA. NASA will be promptly informed of the replacement of other key personnel. Any change in mission objective or in a mission Level 1 requirement will be made only with concurrence from the Program Director at NASA.

For long duration Flagship missions, personnel turnover at all levels can become an issue. Through natural progression people move on to other projects, leave for other opportunities, retire and even pass on. The TSSM staffing plan and long term approach includes backup of key personnel, cross training and continuous training throughout the life cycle of the mission to minimize loss of "corporate knowledge." Steps will be taken during the development phase to ensure that crucial technical information will be captured for use in training in Phase E. A Knowledge capture and Management (KM) system is critical to

ensure technical continuity among personnel from cradle to grave. A system such as that which was developed for New Horizons will be used on TSSM and documented in a Knowledge Capture Plan in Phase B.

4.11.3 Teaming

The Baseline Titan Saturn System Mission would be implemented as a joint NASA/ESA collaborative effort. The team would be composed of members from JPL, JHU/APL, NASA Glenn and ESA/CNES that have complementary strengths as listed in **Table 4.11-1**.

It is expected that NASA will execute a Memorandum of Understanding with ESA that will cover its planned partnership on TSSM, with DOE for delivery of RPS. Preliminary discussions between JPL and APL and JPL and NASA Glenn have been completed. JPL will execute a Memorandum of Agreement with JHU/APL, NASA Glenn, ESTEC and, if necessary, CNES subordinate to the NASA MOUs but at a more detailed level appropriate to project execution. TSSM would comply with all export laws and regulations. Technical Assistance Agreements (TAA) governing technical interchange between the project and international partners are already in place and would be maintained throughout the project development stages to facilitate required interactions.

4.11.4 Roles and Responsibilities

The JPL PM is accountable to the NASA Program Office for the formulation and implementation of the project and for its technical, cost, and schedule performance. The PM will be responsible to the NASA Program Office. The PM would prepare monthly reports to the Program Office and the NASA Management Office (NMO). All element-level management and financial reporting would be through the PM. The PM would also be responsible for the risk management activities of the project. The PM will be supported by a Deputy Project Manager(s), Project Scientist (PS), Project Systems Engineer (PSE), Deputy Project System Engineer, Ground System Manager, Mission Assurance Manager (MAM), Science and Mission Design Manager, Payload Manager, Spacecraft Manager, Launch Services Manager and Business Manager. The Spacecraft Manager will be supported by Orbiter Manager and SEP Stage Manager as well as by a spacecraft system engineer and I&T Lead. Individuals with relevant experience and unique strengths would be appointed to these positions with the goal of building a strong tightly integrated team. Details of the ESA roles and responsibilities below the *In Situ* Element Project Manager and Scientist are discussed in the ESA Assessment Report.

Table 4.11-1. TSSM team member strengths are complementary, reducing risk and ensuring technical readiness.

Team Member	Strengths
JPL	Project Management, Science, System Engineering, Mission Design, Orbiter, Lander, SEP Stage, RPS, Project I&T, Launch services and Ground System
ESA/CNES	Project Management, Science, System Engineering, Mission Design, I&T, Lander, montgolfière , mission ATLO support and Ground System.
JHU/APL	Project leadership, Science, System Engineering, Orbiter, Project I&T support and Ground System support.
NASA Glenn	Qualification and delivery of NEXT thrusters.

The relationships within TSSM will be further established in the next phase. They will include the support of joint or reciprocal announcements of opportunity for the instruments for the NASA orbiter and the *in situ* elements being implemented by ESA.

4.11.5 Work Breakdown Structure

The TSSM WBS is structured to enable effective cost, schedule, and management integration. The WBS is derived from JPL's Standard WBS Version 4 and is fully compliant with Appendix D of NPR 7120.5D. This WBS is a product-oriented hierarchical division of the hardware, software, services, and data required to produce TSSM end products. It is structured according to the way the work would be implemented, and reflective of the way in which project costs, schedule, technical and risk data are to be accumulated, summarized, and reported.

The top level WBS is shown in **Figure 4.11-2.**

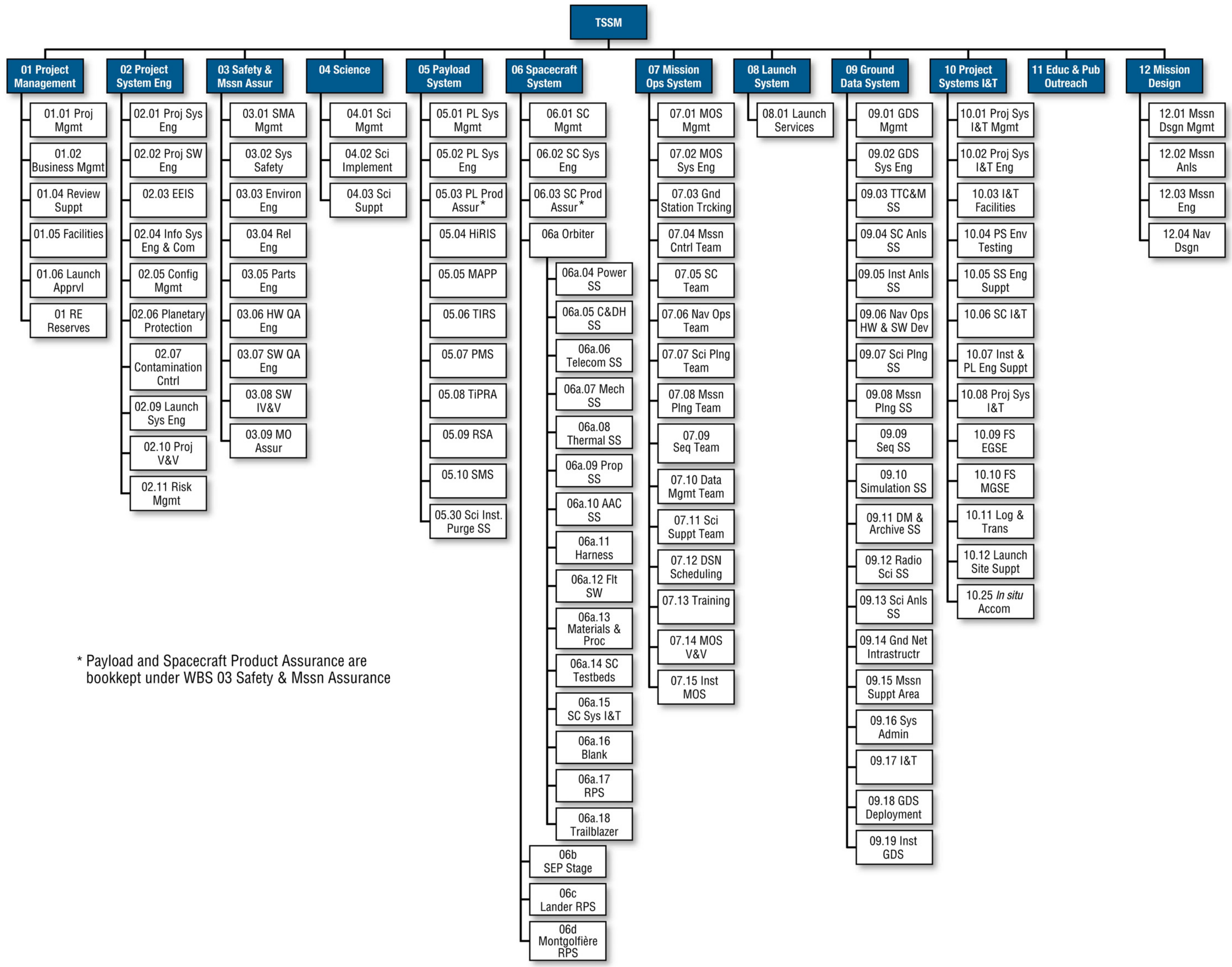


Figure 4.11-2. The TSSM WBS aligns with organizational responsibilities to enable effective cost, schedule, and management integration.

4.11.6 Schedule

The current schedule is based on a September 2020 launch as directed in the NASA Ground Rules for this effort. Numerous other launch opportunities exist (see §4.3.11 and §5.0). TSSM phase durations leading up to launch are the result of a bottoms-up integrated cost/schedule/risk assessment and draws on experience from previous Flagship missions.

4.11.6.1 Pre-Phase A

Up to and including this report, many alternative concept studies have been conducted (Appendix F). Those studies form the basis of an assessment of alternatives that have resulted in the current mission concept and its readiness to complete Pre-Phase A. To complete Pre-Phase A, a pre-project team would be formed to refine the Baseline mission concept and implementation plan in alignment with programmatic goals and objectives. This refinement, including interactions with NASA and ESA and other potential stakeholders, would result in further definition of the mission concept and draft project-level requirements.

Pre-Phase A activities include completion of NPR 7120.5D specified Pre-Phase A Gate Products, preparation of a Project Information Package (PIP) in support of NASA and ESAs coordinated development of Announcements of Opportunity (AO) for instrument acquisition, and a Mission Concept Review leading to Key Decision Point (KDP) A. In addition to those activities required for transition to Phase A, the team has identified additional planning, advanced development and risk reduction tasks that, if funded, would provide a prudent and cost effective approach to early reduction of cost and schedule risk and which have the potential to reduce the estimated cost of Phase A. A preliminary time phased schedule of these tasks is shown in **Figure 4.11-3**. The Flight Readiness Development of NEXT IPS task (see Appendix H) is considered in support of NASA's In-Space Propulsion program and the ASRG task is considered in support of the NASA/DOE ASRG development and qualification program. Time phasing of tasks in the Pre-Phase A schedule is driven by 1) timely completion of Gate Products, AO inputs, and reviews required for transition into Phase A,

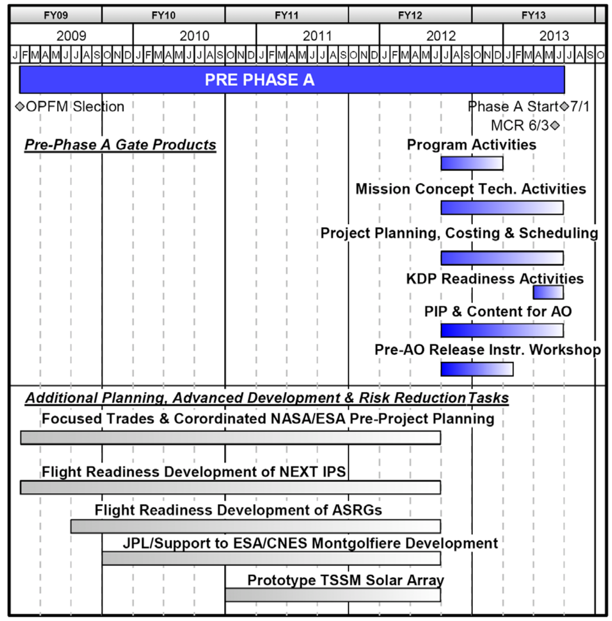


Figure 4.11-3. *Time phasing of Pre-Phase A gate products includes optional planning, advanced development and risk reduction tasks that have the potential to further reduce project A–D cost and risk.*

and 2) completion of selected planning, advanced development and risk reduction tasks prior to start of 1).

4.11.6.2 Phases A through F

The Phase A–F schedule reflects the total project scope of work as discrete and measurable tasks and milestones that are time-phased through the use of task durations, interdependencies, and date constraints and is traceable to the WBS. To insure low risk, the schedule includes funded slack for all tasks. The top level schedule is shown in **Foldout 6** (**FO-6**).

The Project Manager controls the project schedule, with support from a Project Schedule Analyst. An integrated master schedule identifies key milestones, major reviews, and receivables/deliverables (Rec/Dels). Funded schedule reserves shown in the project master schedule for the September 2020 launch opportunity are funded at the peak burn rate, and meet or exceed JPL FPP requirements. The project utilizes an integrated cost/schedule system in Phase B, in order to fully implement an EVM baseline in Phases C/D/E. Inputs will be supplied to NASA's CADRe support contractor for reporting at major reviews.

Schedule and cost estimates at completion (EACs) will be prepared at regular intervals as part of the EVM process. Major project review milestones (not all shown) are consistent with NPD 7120.5D.

Phase A–B

Significant work on Titan mission concepts has been performed over the past 10 years providing a solid basis for initiation of Phase A activities. Since the science objectives have been vetted by the science community several times over the past few years and Cassini-Huygens has completed its Prime mission, it is highly unlikely that significant changes would occur, nor would the implementation response be likely to change significantly as the project moves toward Phase A.

The length of Phases A/B (18 months/18 months) is primarily driven by the schedule to complete Phase A/B Gate Transition Products required by NPR 7120.5D, to produce the instrument Announcement of Opportunity (AO), facilitate selection of instruments, completion of Instrument Concept Design Reviews (ICDR) and advance the project to PDR level of maturity. Early instrument selection allows the instrument designers to work directly with the mission system designers on issues related to accommodation. After each instrument completes its ICDR, the Project assesses the results and presents any updates to the mission concept required to accommodate the conceptual instrument designs. This Instrument Confirmation Review allows both the project and Headquarters the opportunity to adjust implementation details if resources become an issue as a result of the payload selection. Any early work to facilitate the maturation of the instrument implementations would benefit the schedule and reduce project risk.

A milestone for a Planetary Protection Decision has been inserted in Phase B. A basic approach to meeting the planetary protection requirements has been outlined and agreed to by the PPO at NASA Headquarters. This milestone is anticipated to be a review of the more detailed implementation approach including any major outstanding issues related to mission design, Flight System design or operations concepts.

Phases C–D

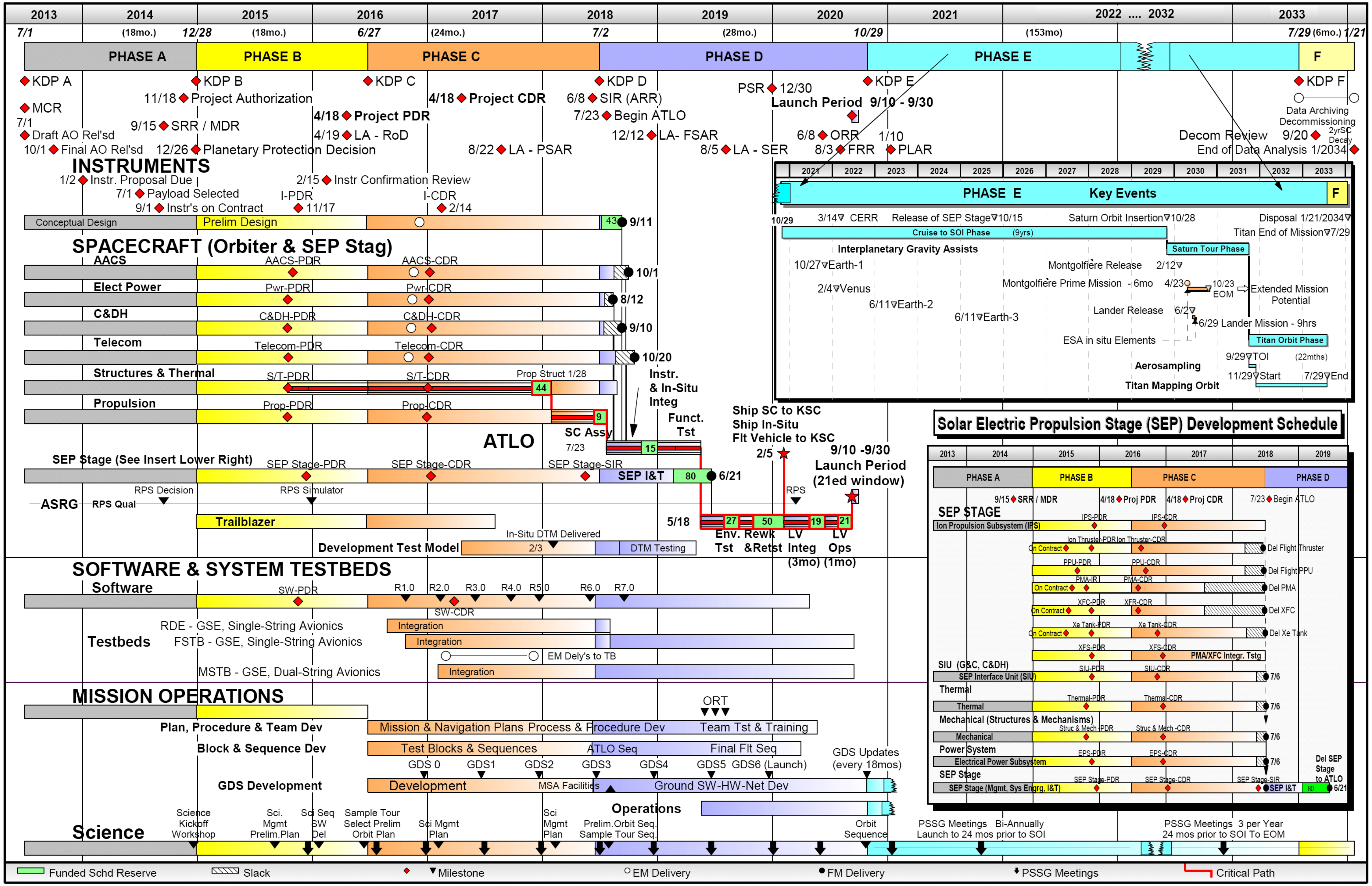
The lengths of Phases C/D (24 months—C, 28 months—D) were developed from a detailed assessment of required tasks and dependencies and compared against Cassini-Huygens experience. These Phases are primarily driven by the schedule to bring the mission system to launch readiness. Phase C is typical for Flagship missions of this complexity. Phase D was developed using the Cassini-Huygens Assembly, Test and Launch and Operations (ATLO) experience. To account for development uncertainties at this stage of maturity, TSSM has included a higher level of schedule and cost reserves for instrument development, SEP IPS development and ATLO than are required in the study Ground Rules and JPL Flight Project Practices.

A trailblazer activity is scheduled to occur at the launch facility to ensure that the spacecraft design is compatible with the launch vehicle and facility limitations at the launch site. These limitations include transportation and loading of the RPSs. This activity starts with planning at a very low level in Phase B and continues with increasing activity until the approach to RPS installation is validated in Phase D. Trailblazer activities make use of Developmental Test Models (DTMs) and also include integration of the MMRTG simulator into the ESA provided montgolfière *in situ* element.

Phases E–F

Phase E (152 months) is driven by the 2020 launch year specified in the study Ground Rules, the interplanetary trajectory and science requirements at Titan, Saturn and Enceladus. Phase F (6 months) is structured to carry out the end-of-mission scenario and to complete data analysis and archiving.

Numerous other launch opportunities exist (See §4.3.11 and §5.0). If a 2018 launch opportunity is preferred, the schedule for the Titan orbiter and SEP stage could be adjusted for the two year advance. Later dates are easily accommodated as well. An ESA baseline schedule was derived during their assessment and delivery of the *in situ* elements is compatible with a 2020 launch. A 2018 launch date also appears to be possible for the ESA elements.


2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 .... 2032 2033
PHASE A
PHASE B
PHASE C
PHASE D
PHASE E
F
KDP A
KDP B
11/18 Project Authorization
KDP C
4/18 Project CDR
KDP D
6/8 SIR (ARR)
7/23 Begin ATLO
PSR 12/30
Launch Period 9/10 - 9/30
KDP E
KDP F
MCR
7/1 Draft AO Rel'sd
10/1 Final AO Rel'sd
9/15 SRR / MDR
12/26 Planetary Protection Decision
4/18 Project PDR
4/19 LA - RoD
8/22 LA - PSAR
12/12 LA- FSAR
8/5 LA - SER
6/8 ORR
8/3 FRR
1/10 PLAR
Data Archiving
Decommissioning
Decom Review 9/20
End of Data Analysis 1/2034
INSTRUMENTS
1/2 Instr. Proposal Due
7/1 Payload Selected
9/1 Instr's on Contract
2/15 Instr Confirmation Review
I-PDR 11/17
I-CDR 2/14
Conceptual Design
Prelim Design
9/11
SPACECRAFT (Orbiter & SEP Stag)
AACS
Elect Power
C&DH
Telecom
Structures & Thermal
Propulsion
10/1
8/12
9/10
10/20
Prop Struct 1/28
Instr. & In-Situ Integ
Funct. Tst
SC Assy
ATLO
SEP Stage (See Insert Lower Right)
SEP Stage-PDR
SEP Stage-CDR
SEP Stage-SIR
SEP I&T
6/21
ASRG
RPS Decision
RPS Qual
RPS Simulator
Trailblazer
In-Situ DTM Delivered
Development Test Model
DTM Testing
Ship SC to KSC
Ship In-Situ
Flt Vehicle to KSC
2/5
9/10 -9/30
Launch Period
(21ed window)
5/18
Env. Tst
Rewk &Retst
LV Integ (3mo)
LV Ops (1mo)
SOFTWARE & SYSTEM TESTBEDS
Software
SW-PDR
SW-CDR
R1.0 R2.0 R3.0 R4.0 R5.0 R6.0 R7.0
Testbeds
RDE - GSE, Single-String Avionics
FSTB - GSE, Single-String Avionics
MSTB - GSE, Dual-String Avionics
Integration
EM Dely's to TB
MISSION OPERATIONS
Plan, Procedure & Team Dev
Mission & Navigation Plans Process & Procedure Dev
Team Tst & Training
ORT
Block & Sequence Dev
Test Blocks & Sequences
ATLO Seq
Final Flt Seq
GDS Development
GDS 0 GDS1 GDS2 GDS3 GDS4 GDS5 GDS6 (Launch)
Development
MSA Facilities
Ground SW-HW-Net Dev
GDS Updates (every 18mos)
Operations
Science
Science Kickoff Workshop
Sci. Mgmt Prelim.Plan
Sci Seq SW Del
Sample Tour Select Prelim Orbit Plan
Sci Mgmt Plan
Prelim.Orbit Seq. Sample Tour Seq.
Orbit Sequence
PSSG Meetings Bi-Annually Launch to 24 mos prior to SOI
PSSG Meetings 3 per Year 24 mos prior to SOI To EOM
PHASE E Key Events
10/29
3/14 CERR
Release of SEP Stage 10/15
Saturn Orbit Insertion 10/28
Disposal 1/21/2034
Titan End of Mission 7/29
Cruise to SOI Phase (9yrs)
Saturn Tour Phase
Interplanetary Gravity Assists
10/27 Earth-1
2/4 Venus
6/11 Earth-2
6/11 Earth-3
Montgolfière Release 2/12
Montgolfière Prime Mission - 6mo 4/23
10/23 EOM
Extended Mission Potential
Lander Release 6/2
6/29 Lander Mission - 9hrs
ESA in situ Elements
Titan Orbit Phase
9/29 TOI (22mths)
Aerosampling
11/29 Start 7/29 End
Titan Mapping Orbit
Solar Electric Propulsion Stage (SEP) Development Schedule
SEP STAGE
Ion Propulsion Subsystem (IPS)
SIU (G&C, C&DH)
SEP Interface Unit (SIU)
Thermal
Mechanical (Structures & Mechanisms)
Power System
Electrical Power Subsystem
SEP Stage
SEP Stage (Mgmt, Sys Engrg, I&T)
Del SEP Stage to ATLO
Funded Schd Reserve
Slack
Milestone
EM Delivery
FM Delivery
PSSG Meetings
Critical Path

Schedule Reserve and Critical Path

The critical path (shown in red on the top-level schedule, **FO-6**) includes the design, test and delivery of the structure and propulsion elements in time to support the ATLO process. Funded schedule reserves of 44 days (9 weeks) for structures, 9 days (2 weeks) for propulsion, 132 days (26 weeks) in ATLO, totaling 185 work days (~37 weeks) have been strategically placed along the critical path. The costs for these reserves are included in the Baseline plan and estimated based on the peak-spending rate during the phase of the project to which the reserves apply.

TSSM's critical path is similar to what was experienced on Cassini-Huygens and would be further mitigated during Phases A and B by more detailed design, test and integration planning. TSSM development plans include maximum use of early prototypes and testing during Phases A and B to reduce instrument and subsystem development risk keeping them off the critical path.

4.11.7 Estimated Mission Cost

The TSSM cost estimate presented here is the total mission cost to NASA for the complete project life cycle from Phase A through Phase F. Pre-Phase A costs are discussed and reported separately.

4.11.7.1 Cost Estimating Methodologies

The cost estimating methodologies used to develop the TSSM cost estimate are described in **Table 4.11-2**. This TSSM cost estimate was developed based on a hybrid methodology consisting of JPL institutional cost models developed by JPL's implementing organizations, the subsystem NASA Instrument Cost Model (NICM), grassroots cost estimates developed by technical leads, and percentage wrap factors derived from cost rules of thumb and cost analogies. Launch Services, DSN Aperture, and Radioisotope Power System costs were provided by NASA Headquarters. **Figure 4.11-4** summarizes the cost share percentage by estimation method for the NASA/ESA Baseline.

4.11.7.2 Pre-Phase A Costs

A description of Pre-Phase A tasks and a preliminary time phased plan is described in §4.11.6.1. A time phased breakout of cost on a task basis is shown in **Table 4.11-3**.

To complete Pre-Phase A, a pre-project team would be formed to refine the Baseline mission concept and implementation plan in alignment with programmatic goals and objectives. This refinement, along with interactions with NASA, ESA and other potential stakeholders, would result in further definition of the mission concept and DRAFT project-level requirements. Activities are also included to prepare a Project Information Package (PIP) in support of coordinated NASA and ESA Announcements of Opportunity (AO) for instrument acquisition. Pre-Phase A activities will complete NPR 7120.5D specified Pre-Phase A Gate Products, preparation of PIP for instrument AO, and a Mission Concept Review leading to Key Decision Point (KDP) A.

In addition to those activities required for transition to Phase A, the team has identified additional planning, advanced development and risk reduction tasks that, if funded, would provide a prudent and cost effective approach to early reduction of cost and schedule risk and which have the potential to reduce the estimated cost of Phase A. If NASA elects not to fund the additional planning, advanced development and risk reduction tasks, the total mission cost and cost reserve plan proposed herein would be preserved.

The Baseline plan presumes that the Pre-Phase A risk reduction work does not occur, however the funding for the Gate Products, preparation of a Project Information Package (PIP) in support of NASA's development of an Announcement of Opportunity (AO) for instrument acquisition, and a Mission Concept Review leading to Key Decision Point (KDP) A would be needed.

The TSSM project highly recommends that NASA support early risk reduction activities for instruments in the period from FY09 up to the start of Phase A. Costs for this activity are not included in the TSSM estimate.

Table 4.11-2. *Cost estimating methodology.*

BS Element	Description
01 Project Management	Institutional cost models. The estimate was augmented for TSSM specific implementation characteristics such as additional DPM to work with ESA on accommodation of the *in situ* elements and a CTM for the APL subcontract. WBS 01.06 Launch Approval was estimate using grassroots methodology.
02 Project System Engineering	Institutional cost models. The estimate was augmented for TSSM specific implementation characteristics such as additional Deputy PSE to coordinate with ESA on accommodation of the *in situ* elements. WBS 02.06 Planetary Protection estimated using grassroots methodology.
03 Safety & Mission Assurance	Percentage wrap factor. Phase A–D = 5.0%, Phase E = 2.0% of CBE cost excluding RPS and LV. Includes Project level SMA and Spacecraft System product assurance. Instrument specific PA is included in the NICM estimate.
04 Science	Institutional cost model. The estimate was verified and reconciled by the TSSM Project Scientist against actual costs from previous Cassini, Galileo and other projects.
05 Payload System	Institutional cost models for WBS 05.01 P/L Mgmt and 05.02 P/L SE. NICM subsystem model was used to develop the instrument costs. Source: *NICM Version 1 -- Released December 2006*. Individual instrument cost estimates include instrument specific Management, System Engineering, Product Assurance and Integration & Test.
06 Spacecraft System	Grassroots estimate to WBS level 4 and below. Estimates developed and reviewed by technical line and project management organizations.
Radioisotope Power Systems (orbiter, lander, and montgolfière)	Source: *RPS Cost Estimate for Flagship_v4*, 4/10/2007
07 Mission Ops System	Institutional cost models.
07.03 DSN Aperture	DSN aperture fee estimated using *DSN Aperture Fee* tool. The *DSN Aperture Fee* tool is imbedded within the Institutional cost model for 07 Mission Operations System.
08 Launch System w/ Nuclear Support	Source: *Requirements and Ground rules for Flagship Mission Studies*, Table 1 ROM Launch Services costs for Atlas V and Delta IV Heavy launch vehicles. Table values reported in $FY06 and escalated to $FY07 dollars. Includes nuclear payload costs.
09 Ground Data System	Institutional cost models.
10 Project System I&T	Grassroots estimate to WBS level 4. Estimates developed and reviewed by technical line and project management organizations.
11 Education and Public Outreach	Percentage wrap factor. Phase A = 0.5%, Phase B / D = 0.5%, and Phase E / F = 2.0% of base.
12 Mission Design	Grassroots estimate. Estimates developed and reviewed by technical line and project management organizations.
Reserves	Reserve base excludes LV, DSN Aperture, and EPO. Phase A—10%, Phase BCD— 35%, Phase E—15%.

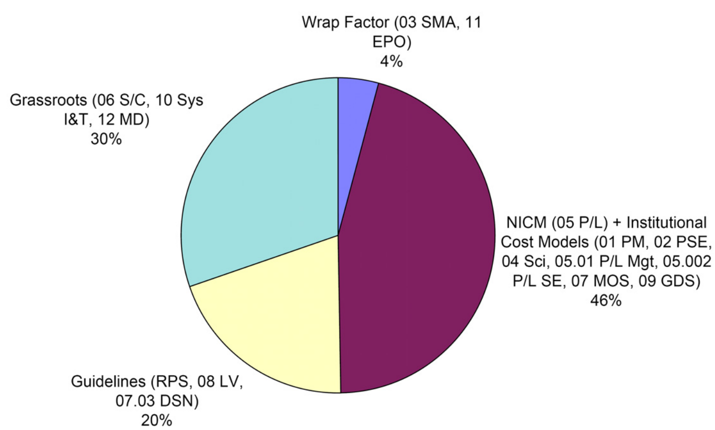


Figure 4.11-4. *Cost percentage by estimation method (excluding reserves).*

Table 4.11-3. *Cost estimate for Pre-Phase A gate products and optional planning, advancement development, and risk reduction tasks.*

Activity		Task Description		FY 2009	FY 2010	FY 2011	FY 2012	FY 2013	Total $k (RY)	Work Years
Pre-Phase A Gate Products	1	**Program Activities**	Approved FAD, DRAFT Program Requirements on Project	$0	$0	$0	$220	$101	**$321**	**0.98**
	2	**Mission Concept Technical Activities**	Preliminary Mission Concept Report, MCR Review	$0	$0	$0	$1,868	$8,314	**$10,181**	**30.96**
	3	**Project Planning, Costing and Scheduling**	DRAFT Integrated Baseline: WBS, Schedule, Cost, Technology Assessment, Infrastructure and WF needs assessment, identification of partnerships, acquisition strategy for major procurements	$0	$0	$0	$427	$1,236	**$1,663**	**5.06**
	4	**KDP Readiness Activities**	SRB Report, PM Recommendation, CMC Recommendation, GPMC Review	$0	$0	$0	$0	$603	**$603**	**1.83**
	5	**PIP and content for AO**	PIP; NASA AO; ESA AO Coordinate with ESA in release of their AO.	$0	$0	$0	$256	$741	**$998**	**3.04**
	6	**Pre-AO release Instrument Workshop**	Workshop announcement; workshop; report to SMD	$0	$0	$0	$85	$101	**$186**	**0.57**
	Total Pre-Phase A Gate Products Cost:			**$0**	**$0**	**$0**	**$2,856**	**$11,095**	**$13,952**	**42.44**
Advanced Planning, Development and Risk Reduction	7	**Focused Trades and Coordinated NASA/ESA Pre-Project Planning**	Preliminary development of NASA/ESA responsibility assignments, schedule, cost, and overall project plan.	$1,106	$1,410	$1,343	$982	$0	**$4,841**	**16.67**
	8	**Flight readiness development of NEXT IPS**[1]	EM PPU, Qual Model thruster	$3,679	$6,634	$4,496	$1,811	$0	**$16,620**	**28.09**
	9	**Flight readiness development of ASRG**[1]	ICD based on flight qualified ASRG.	$36	$151	$155	$201	$0	**$543**	**1.74**
	10	**JPL support to ESA/CNES montgolfière development**	Consult/collaborate with CNES on flight-like deployments, altitude control, high-fidelity performance simulations and estimates, improved design models, extended thermal testing of montgolfière materials	$0	$60	$155	$240	$0	**$455**	**1.44**
	11	**Prototype TSSM solar array**	TSSM solar array prototype from ATK.	$0	$0	$621	$480	$0	**$1,100**	**3.47**
	Total Optional Advanced Planning, Development and Risk Reduction:			**$4,821**	**$8,255**	**$6,770**	**$3,714**	**$0**	**$23,561**	**51.42**
Total Pre-Phase A Estimate:				**$4,821**	**$8,255**	**$6,770**	**$6,571**	**$11,095**	**$37,513**	**93.85**

[1] The Flight Readiness Development of NEXT IPS and ASRG tasks are consistent with NASA's currently funded development programs

4.11.7.3 Baseline (and NASA-only) Lifecycle Cost Estimate

The current TSSM Phase A through F lifecycle cost estimate for the NASA/ESA Baseline mission architecture that includes the NASA orbiter, SEP stage and accommodation and support for the ESA-provided lake lander and montgolfière is estimated at a cost to NASA of $3.71B (RY) or $2.53B (FY07). This does not include ESA's cost for contributed *in situ* elements, nor does it account for potential cost reductions to NASA which might occur if instruments or hardware, as described in Appendix G, are furnished by a foreign entity or ESA member states.

The costs to ESA are commensurate with the budget envelope for an L-class mission of the Cosmic Vision 2015–2025 program (650M€ Cost-at-Completion). These ESA costs do not include the development and delivery of the balloon envelope for the montgolfière aerial vehicle, which would be provided by CNES as stated in the CNES letter of commitment in Appendix M. Furthermore the provision of science instruments is expected from European national funding, and is therefore also not included in ESA's costs.

The WBS Level 3 summary for the TSSM NASA/ESA Baseline mission is reported in **Table 4.11-4** by project phase.

In the case where there is an ESA decision not to participate (the Cosmic Vision Programme outer planet decision is planned to occur prior to Phase A), TSSM could proceed as a NASA-only mission. The NASA-only mission costed in this study includes the orbiter and SEP stage and is estimated at $3.59B (RY) or $2.44B (FY07). The cost summary for the TSSM NASA-only mission is reported in **Table 4.11-4**. NASA may still wish to consider the possibility of incorporating an *in situ* payload, however that option was beyond the scope of the study and is not included in the NASA-only mission described here.

The TSSM cost estimate represents the full lifecycle cost and conservatively assumes individual instruments instead of instrument suites. The TSSM cost also includes a conservative 50% cost reserve on the instruments, SEP stage NEXT IPS and ATLO.

A technical characterization of TSSM is given in **Table 4.11-5**.

4.11.7.4 Budget Reserve Strategy

Budget reserves were established using bottoms-up and top-down methodologies based on previous experience. As determined from the methodologies mentioned above, the TSSM budget reserves are calculated as:

- Phase A = 10%
- Phase B through D = at 35% per bottoms up analysis. The top-down analysis yielded a 34% estimate.
- Phase E = 15%

The reserve base is the current best estimate cost including RPS but excludes DSN Aperture, Launch System, and Education & Public Outreach.

Reserves status will be evaluated at project key decision points. Commensurately, the confidence in implementing the mission within the overall estimate provided here is expected to grow.

4.11.7.5 Cost of *In Situ* Accommodation

Included in the TSSM NASA/ESA cost estimate is the cost directly associated with accommodating the ESA provided lake lander and montgolfière. The study team defined the *in situ* element resource needs and orbiter interface requirements to identify accommodations required specifically for the delivery and support of ESA provided *in situ* elements as described in Appendix I. As a result, costs associated with accommodation of the ESA-provided *in situ* elements were clearly identified in each of the cost estimates generated for each affected WBS element. These costs are presented in **Table 4.11-6**. Subtracting the costs associated with the accommodation indicates a savings of $119M (RY) between the NASA/ESA Baseline and NASA-only missions. This represents the incremental cost impact to NASA resulting from accommodation of the ESA *in situ* elements.

Table 4.11-4. *TSSM NASA/ESA Baseline cost summary by project phase and TSSM NASA-only mission total cost summary.*

WBS Element	TSSM Project Phase A	B	C	D	Subtotal Phase A–D	TSSM Project Phase E	F	NASA/ESA Baseline $M RY	NASA/ESA Baseline $M FY07	NASA-only Mission $M RY	NASA-only Mission $M FY07
Phase Duration (Mos.)	**18**	**18**	**24**	**28**	**88**	**152**	**6**				
01 Proj Mgmt	9.2	30.8	40.2	35.0	115.1	67.7	0.6	183.4	122.5	182.1	121.6
02 Proj Sys Eng	3.9	9.0	15.7	20.2	48.7	11.1	0.1	59.8	40.8	58.2	39.6
03 Safety & Mssn Assur	3.8	18.1	42.7	22.1	86.7	12.9	0.9	100.5	73.1	100.5	73.1
04 Science	1.5	8.3	31.3	19.8	61.0	220.6	13.3	294.8	158.3	294.8	158.3
05 Payload System	2.0	25.1	203.9	66.0	297.1			297.1	221.8	297.1	221.8
05.01 PL Sys Mgmt	1.5	1.7	2.7	3.4	9.3			9.3	6.7	9.3	6.7
05.02 PL System Eng	0.5	2.7	5.5	5.1	13.7			13.7	9.9	13.7	9.9
05.04 HiRIS	-	4.4	41.3	12.2	57.8			57.8	43.3	57.8	43.3
05.05 MAPP	-	2.9	27.1	8.0	37.9			37.9	28.4	37.9	28.4
05.06 TIRS	-	3.5	33.4	9.9	46.8			46.8	35.0	46.8	35.0
05.07 PMS	-	2.5	23.4	6.9	32.8			32.8	24.5	32.8	24.5
05.08 TiPRA	-	4.4	42.0	12.4	58.8			58.8	44.0	58.8	44.0
05.10 SMS	-	3.0	28.1	8.3	39.4			39.4	29.5	39.4	29.5
05.30 Sci Inst. Purge	-	0.0	0.6	-	0.6			0.6	0.4	0.6	-
06 SC System	49.3	234.0	397.7	123.6	804.6			804.6	601.7	775.5	580.1
06.01 SC Mgmt	1.8	2.4	3.4	4.3	11.9			11.9	8.5	11.8	8.5
06.02 SC Sys Eng	4.7	14.0	18.8	13.1	50.6			50.6	37.3	45.7	33.7
06a Orbiter	40.9	180.7	291.5	83.8	596.9			596.9	447.1	572.7	429.1
06a.04 Power SS	2.5	21.4	30.4	4.0	58.3			58.3	44.3	58.3	44.3
06a.05 C&DH SS	3.9	27.4	24.4	1.8	57.6			57.6	44.2	57.6	44.2
06a.06 Telecom SS	14.6	36.4	28.1	5.5	84.6			84.6	65.2	76.5	58.7
06a.07 Mech SS	2.7	29.5	93.7	13.2	139.0			139.0	103.3	137.5	102.1
06a.08 Thermal SS	2.8	10.0	12.3	8.3	33.4			33.4	24.8	31.2	23.2
06a.09 Prop SS	8.0	24.8	17.0	7.1	57.0			57.0	43.3	57.0	43.3
06a.10 GN&C SS	5.5	20.8	36.2	7.9	70.5			70.5	52.9	70.5	52.9
06a.11 Harness	0.1	2.0	7.8	4.2	14.1			14.1	10.3	14.1	10.3
06a.12 Flt SW	0.4	6.3	28.6	23.2	58.6			58.6	41.8	47.9	34.2
06a.13 SC Materials & Proc	0.2	1.0	2.3	0.9	4.3			4.3	3.2	4.3	3.2
06a.14 SC Testbeds	-	1.1	8.7	6.3	16.2			16.2	11.6	16.2	11.6
06a.18 DTM	-	-	1.9	1.3	3.3			3.3	2.3	1.6	1.2
06b SEP Stage	1.9	36.9	84.1	22.4	145.3			145.3	108.8	145.3	108.8
07 Mission Ops Sys	1.9	6.4	17.0	40.4	65.7	352.5	5.9	424.1	230.0	424.1	230.0
09 Ground Data Sys	2.3	5.6	17.9	28.9	54.6	43.8	0.6	99.0	62.8	99.0	62.8
10 Project Sys I&T	0.3	6.2	16.3	44.4	67.3	-	-	67.3	47.7	67.3	47.7
11 Ed & Pub Outreach	0.4	1.7	3.9	2.0	8.0	13.2	0.4	21.6	13.6	21.6	13.6
12 Mission Design	5.4	6.5	7.6	9.1	28.5	-	-	28.5	21.2	28.5	21.2
CBE Cost	**80.1**	**351.7**	**794.2**	**411.4**	**1,637.3**	**721.8**	**21.8**	**2,380.8**	**1,593.6**	**2,348.8**	**1,569.8**
Reserves	8.0	134.1	316.9	166.0	624.9	106.3	3.2	734.4	518.3	708.0	497.7
CBE + Reserves	**88.1**	**485.8**	**1,111.0**	**577.4**	**2,262.2**	**828.0**	**25.0**	**3,115.2**	**2,111.8**	**3,056.7**	**2,067.5**
06a.17 Orbiter RPS	-	21.9	83.5	47.1	152.5			152.5	114.0	152.5	114.0
06b Lander RPS	-	1.6	-	-	1.6			1.6	1.2	-	-
06c Montgolfière RPS	-	9.8	31.5	17.8	59.1			59.1	44.2	-	-
DSN Aperture	-	-	-	3.5	3.5	107.5	-	111.0	58.1	111.0	58.1
Launch System	-	-	132.4	136.1	268.4	-	-	268.4	197.1	268.4	197.1
Total Mission Cost	**88.1**	**519.1**	**1,358.4**	**781.8**	**2,747.4**	**935.5**	**25.0**	**3,707.9**	**2,526.5**	**3,588.7**	**2,436.7**

- WBS element 05.03 Payload Product Assurance is costed under WBS element 03 Safety & Mssn Assur
- WBS element 05.09 RSA is costed under WBS element 06a.6. Telecom SS
- WBS element 06.03 Spacecraft Product Assurance is costed under WBS element 03 Safety & Mssn Assur
- WBS element 06a.16 is unallocated
- WBS element 06a.15 Spacecraft System I &T is costed under WBS element 10.0 Project Sys I &T

Table 4.11-5. Summary technical characterization of Titan Saturn System Mission.

	TSSM Mission Characteristic
Launch Date	September 2020
Trajectory	EVEEGA
Launch Vehicle	Atlas V 551
Flight Elements	Orbiter, SEP stage, ESA *in situ* elements
RPS	5 Flight ASRGs + 1 Flight Spare, 1 MMRTG, RHUs
Instruments Quantity	7, including Radio Science
Mission Duration: Saturn Tour Phase/Titan Orbit Phase	4 years combined
Reserve on Phases B–D	35%

4.11.7.6 Cost of *Planetary Protection*

Planetary protection requirements on the orbiter would be met with common cleaning and handling procedures as well as end of mission trajectory control and would not require the added cost of dry heat microbial sterilization or bio-barriers. The *in situ* elements would be the responsibility of ESA. Analysis is planned and costed under WBS element 02, Project Systems Engineering, to demonstrate that the approaches described above meet planetary protection requirements.

4.11.7.7 Phase E Cost Reductions

One of the key goals of this study was to explore ways of reducing the costs of Phase E operations significantly below the level experienced by the Cassini-Huygens mission. As part of the OPFM effort, a study was conducted (Appendix K: Mission Operations Lessons Learned Study for The Next Outer Planet Flagship Mission) to assess lessons learned from Cassini, New Horizons, MRO and MESSENGER mission operations experience with the intent to improve efficiency and lower the cost of operating the next OPFM. Results from that study (as shown in Appendix K) were incorporated in the TSSM design and have dramatically reduced the complexity and therefore cost of mission operations. A particularly striking example is the incorporation of a gimbaled high gain antenna which decouples science from telecommunications allowing for much simpler science planning and sequence operations and therefore lower cost (i.e., scan platform lessons learned on Cassini). Another example is the pre-set repetitive sequence of

Table 4.11-6. In situ accommodation cost.

WBS Element	NASA/ESA Baseline ($M RY)	NASA-only Mission ($M RY)	Accommodation Cost
01 Proj Mgmt	183	182	1
02 Proj Sys Eng	60	58	2
03 Safety & Mssn Assur	101	101	-
04 Science	295	295	-
05 Payload System	297	297	-
06 Spacecraft System	805	775	29
07 Mssn Ops Sys	424	424	-
09 Ground Data Sys	99	99	-
10 Project Sys I&T	67	67	-
11 Educ & Pub Outreach	22	22	-
12 Mission Design	29	29	-
CBE Cost	2,381	2,349	32
Reserves	734	708	26
CBE + Reserves	3,115	3,057	59
06A.17 Orbiter RPS	153	153	-
06C Lander RPS	2	-	2
06D Balloon RPS	59	-	59
DSN Aperture	111	111	-
Launch System	268	268	-
Total Mission Cost	**3,708**	**3,589**	**119**

instrument operations for the Titan orbit period where all measurements are made without frequent replanning, science team negotiations and resequencing of the mission.

These efforts assume a modern approach to mission operations and supporting software systems similar to Cassini and MRO. **Table 4.11-7** provides a comparison of the TSSM Phase E burdened cost estimate by year to the Cassini actual Phase E costs normalized to $M (FY07). For comparison, the time series of cost aligns Cassini's SOI event with TSSM's SOI event so similar phases can be compared. A significant difference between TSSM and Cassini's operations cost is that Cassini's design with a fixed antenna and 12 body-mounted instruments resulted in an extremely complex operations planning and sequencing process that required extensive negotiations and iterations among many large teams.

For the long Interplanetary Cruise Phase, TSSM saves nearly $40M (FY07)/yr in operations costs because of the quiet cruise characterized by very limited instrument calibration

Table 4.11-7. *Comparison of TSSM and Cassini Phase E costs aligned at similar SOI events.*

TSSM Fiscal Year	TSSM Phase E ($M FY07)	Cassini ($M FY07)	Cassini-Huygens Fiscal Year
2021	$33	N/A	1996
2022	$31	N/A	1997
2023	$29	$46	1998
2024	$24	$82	1999
2025	$25	$65	2000
2026	$22	$69	2001
2027	$20	$77	2002
2028	$21	$80	2003
2029	$31	$88	2004
2030	$34	$84	2005
2031	$56	$76	2006
2032	$56	$84	2007
2033	$45	$58	2008

1. TSSM launch: September FY2020
2. Cassini SOI = June 30, 2004
3. TSSM SOI = September 21. 2029
4. TSSM TOI = September 29, 2031

and operations training activities leading up to one year prior to SOI. TSSM operations cost has been significantly reduced at ~$34M (FY07)/yr for the Saturn Tour Phase compared to ~$84M (FY07)/yr for Cassini tour operations. This results in a planned savings of ~$50M (FY07)/yr which is due to prior mission Phase E lessons learned as well as reduced activity associated with TSSM's focused instrument set which is half the number carried on the Cassini orbiter and tour operations focused on Titan and Enceladus only. Titan orbital operations are ~$25M (FY07)/yr less expensive than Cassini tour operations for these reasons as well as the simplified repetitive sequencing of Titan orbit operations. Further reductions are likely as more detailed analysis and planning are completed.

Still to be exploited are methods and technologies from continuing advancements, which are poised to make sizable savings in the cost of mission operations. There will be a two-decade gap between the capabilities of Cassini during development and those of TSSM for the same phase. This is as large as the gap between Voyager and Cassini, which saw huge gains in productivity and capability. With the progress that has been made since Cassini and New Horizons, largely through continuing institutional investments, it is expected that it will possible to reliably streamline operations processes and improve spacecraft operability and robustness, resulting in direct reductions in complexity and staffing levels, the major component of operations cost.

The steps envisioned to enable this improvement start with new architectural methods during development that use operations scenarios and system models to more transparently specify and shape software design for both ground and Flight Systems. This has been demonstrated to reduce incidental complexity, producing designs that are more easily understood, and easier to validate and operate. Additional architectural support will be provided through upgraded ground system service infrastructure and middleware, as well as improvements in visualization and analysis tools, and more. Improved planning and validation tools are also available, with flight-proven success in substantially reducing cost.

Together, such capabilities enable a more consolidated and collaborative operations approach, with fewer hand-offs and translations, simpler interfaces, and better automation of routine functions. And on board, they translate into a more trouble-free spacecraft that requires less supervision, and can be used flexibly to meet the scientific objectives of the mission.

The additional savings to be gleaned from such an approach will require further study to quantify. Still, even modest reductions in operations cost accumulated across several years of Phase E can yield significant savings compared to the investments anticipated to leverage available innovations during Phases B/C/D. With such economies readily available to this project in the time frame of its development, TSSM is positioned well to achieve ambitious goals for low operations cost.

4.11.7.8 Descope Strategy

This mission concept provides descope options for both NASA and ESA to a scientifically attractive "NASA/ESA Floor" mission (see §3.3.1.2 and **Figure 3.1-1**), yielding a very robust project implementation plan. In the event that demand on project reserves is higher than planned, meaningful descopes would be available to replenish reserves during the development phases. A preliminary list of potential descopes has been identified along with their associated mass and cost savings if

Table 4.11-8. *TSSM NASA/ESA floor and NASA-only floor descopes, costs in $M RY and $M FY07.*

Potential Descope List (not in priority order)	Impact	Savings at: kg fully margined	PDR $M RY	PDR $M FY07	CDR $M RY	CDR $M FY07
Eliminate engine cover	Risk of main engine coating damage from micrometeoroid debris	8	$9	$7	$8	$6
Remove Pre-Launch ASRG Spare	Schedule delay if one of the ASRGs fails prior to launch. Mitigated by back up option.	N/A	$40	$26	$35	$22
Remove OpNav Camera	Less navigation accuracy drives higher Enceladus flyby altitudes.	10	$10	$8	$4	$3
Reduce Titan circular orbit from 20 months to 14 months	Reduces the number of color maps to 3 from 4.	N/A	$79	$38	$79	$38
Replace NEXT IPS with BPT4000 Hall thrusters of XIPS thrusters	Increase in trip time. Reduced thruster cost balanced by increased trip time results in no net cost savings.	N/A	$0	$0	$0	$0
Remove SEP stage	Increased trip time that would extend mission duration beyond 14 years without reducing Titan circular orbit duration by 6 months (see descope above).	1229	$73	$66	$18	$25
	Total Potential Descopes	**1247**	**$213**	**$145**	**$144**	**$94**

exercised at the time of the project PDR or CDR as shown in **Table 4.11-8**. The actual descope path in going from the Baseline mission to the Floor mission could follow a number of sequences depending on the reason the descope would be required. Decisions based on risk might be different from those driven by cost or mass. Thus, an approach would be developed that quantifies the impact of each descope on the mission. This would be done in conjunction with the implementation team and HQ. Once defined, impact on the mission can be traded against science, risk, schedule, and cost. This approach would be implemented by the Project System Engineering Team to ensure that optimal descope decision options are made and communicated to the sponsor, stakeholders, and team.

Transition to a viable NASA-only mission can occur at any point in any descope sequence from the Baseline mission to the NASA/ESA Floor mission, and at any time. The trigger for adopting the NASA-only option would be ESA's decision not to participate.

As described in §2.4.2, the JSDT has defined a planning payload with model instruments for purposes of conducting this study. The study team determined that the most cost effective descopes were those presented in **Table 4.11-8**. Assessment indicates that descoping a model instrument would have a large impact on science with very little savings in cost, mass or power. When the actual payload is selected as a result of the AO process, the project descope plan will be revisited to assess possible instrument descopes. A complete prioritized descope list and time-phased descope plan would be established in Phase B prior to confirmation and approval to proceed. Only the PM would be able to authorize descopes with the concurrence of the PS and HQ. If a level 1 requirement is effected, then HQ approval is required.

4.11.7.9 Floor Mission Costs

The NASA/ESA Baseline and the NASA-only mission could be fully descoped, as shown in **Tables 4.11-8** and **4.11-9**, which includes, among other things, removing the SEP stage from the mission architecture. A fully descoped NASA/ESA Floor mission is estimated at $3.29B (RY) and the NASA-only Floor mission is estimated at $3.17B (RY). This assumes that all descopes would have been taken by Project PDR.

Table 4.11-9. Comparison between Baseline, Floor, and NASA-only costs.

Mission Option	$M RY	$M FY07
NASA/ESA Baseline	3,708	2,527
NASA/ESA Floor	3,293	2,281
NASA-only Mission	3,589	2,437
NASA-only Floor	3,174	2,191

4.11.7.10 Early Launch Options

As shown in §4.3.11, there is a pair of attractive launch opportunities in 2018 and 2019 that both arrive in early 2028, 14 months earlier than the Baseline September 2020 launch. If NASA and ESA were to decide to launch TSSM during the 2018 opportunity (with a 2019 backup), the schedule could be shifted to accommodate that decision. The NASA study indicates that the orbiter, SEP stage and other NASA mission elements can meet this delivery schedule and ESA's assessment study indicates likewise for delivery of the *in situ* elements. This would require that preparation of the AO and all Pre-Phase A Gate Product activities be initiated earlier than what is shown in **Figure 4.11-3**; this is easily accommodated by the time period between the completion of this study and the start of Phase A. No changes to the fixed year cost estimate for A–F would be identifiable as the interplanetary trajectory would be the same length. In real year dollars, the cost would be lowered by 14 months of inflation.

As described in §3.3.2.4, NASA and ESA also have an alternate option of launching the orbiter prior to 2018 with ESA separately launching the *in situ* elements up to several years later with opportunities that recur every year. This alternative approach would result in moderate increases in fixed year costs to both NASA and ESA.

4.11.8 Risk Assessment and Management Strategy

As a Category 1, Class A mission, TSSM baselines a risk manager at the mission level reporting to the project office. Risk identification and assessment is part of the daily management and systems engineering process, with all team members as active participants. All technical and programmatic margins carried on TSSM currently exceed JPL and JHU/APL requirements and are prudent for a Pre-Phase A study. Starting in Phase A, all technical, management and cost margins and reserves will be aggressively managed.

In the event of unforeseen problems, a descope strategy (outlined in §4.11.7.8) has been developed for keeping the project within cost and schedule constraints without falling below the science floor. The TSSM risk assessment (**Figure 4.10-1**), including all moderate and high risks, is summarized in §4.10 and was performed using the criteria shown in **Table 4.10-1**. The risk management process initiated for this study contains the key aspects that would be used during formal mission formulation and development. The Risk Manager monitors the common risks associated with staffing, technology, cost, schedule, and perception. Four primary activities are performed in the risk management process:

1. Risk identification: A continuous effort to identify and document risks as they are found and to provide an estimation of the risk attributes (i.e., the consequences of failing to achieve a desired result and the likelihood of failing to achieve that result)
2. Risk analysis: An evaluation of the submitted item to determine whether or not it qualifies as a project risk and a decision about what to do with the risks, which, for important risks, includes mitigation plans
3. Risk assessment: The process used to prioritize risks relative to each other (creation of the Risk Watch List)
4. Risk handling: Tracking and controlling risks—collecting and reporting status information about risks and their mitigation plans (where appropriate) and taking corrective action as needed (maintenance of the Risk Management Database).

The Risk Manager (RM) is responsible for implementing the Risk Mitigation Plan. At the project level, risks are tracked and reported through use of a database and all moderate and high risks are carried on the Risk Watch List to facilitate communication. The Project Manager has the ultimate responsibility for project risk. As such, a risk management process will be put in place in Pre-Phase A and will monitor progress at least weekly as mitigation of these risks is most effective early in the project. Risk

Manager role will be staffed in Pre-Phase A. The Safety and Mission Assurance organization will be utilized for independent assessment of the process.

4.11.9 NEPA Compliance and Launch Approval

Environmental review requirements will be satisfied by the completion of a mission-specific Environmental Impact Statement (EIS) for the TSSM mission. In accordance with the requirements described by NPR 7120.5D, the Record of Decision (ROD) for this EIS would be finalized prior to or concurrent with Project PDR.

The TSSM launch approval engineering (LAE) Plan will be completed no later than the Mission Definition Review (MDR). This plan will describe the approach for satisfying NASA's NEPA requirements for the TSSM mission, and the approach for complying with the nuclear safety launch approval process described by Presidential Directive/National Security Council Memorandum #25 (PD/NSC-25) and satisfying the nuclear safety requirements of NPR 8715.3. The LAE Plan will provide a description of responsibilities, data sources, schedule, and an overall summary plan for preparing:

- A mission-specific environmental review document and supporting nuclear safety risk assessment efforts;
- Launch vehicle and Flight System/mission design data requirements (including Earth Swingby Assessment) to support nuclear risk assessment and safety analyses in compliance with the requirements of NPR 8715.3 and the PD/NSC-25 nuclear safety launch approval process;
- Support of launch site radiological contingency planning efforts; and
- Risk communication activities and products pertaining to the NEPA process, nuclear safety and planetary protection aspects of the project.

It is anticipated that NASA HQ will initiate the TSSM environmental review document development as soon as a clear definition of the Baseline plan and option space has been formulated. DOE would provide a nuclear risk assessment to support the environmental review document, based upon a representative set of environments and accident scenarios compiled by the KSC/Launch Services Program working with JPL. This deliverable may be modeled after the approach used on the Mars Science Laboratory (MSL) EIS.

DOE will provide a nuclear safety analysis report (SAR) based upon NASA-provided mission-specific launch system and Flight System data to support the PD/NSC-25 compliance effort. The SAR would be delivered to an ad hoc interagency nuclear safety review panel (INSRP) organized for the TSSM mission. This INSRP would review the SAR's methodology and conclusions and prepare a Safety Evaluation Report (SER). Both the SER and the SAR would then be provided by NASA to EPA, DoD, and DOE for agency review. Following agency review of the documents and resolution of any outstanding issues, NASA, as the sponsoring agency, would submit a request for launch approval to the Director of the Office of Science and Technology Policy (OSTP). The Director of the OSTP would review the request for nuclear safety launch approval and either approve the launch or defer the decision to the President. Key dates and deliverables for the NEPA and nuclear safety launch approval processes are shown in **FO-6**.

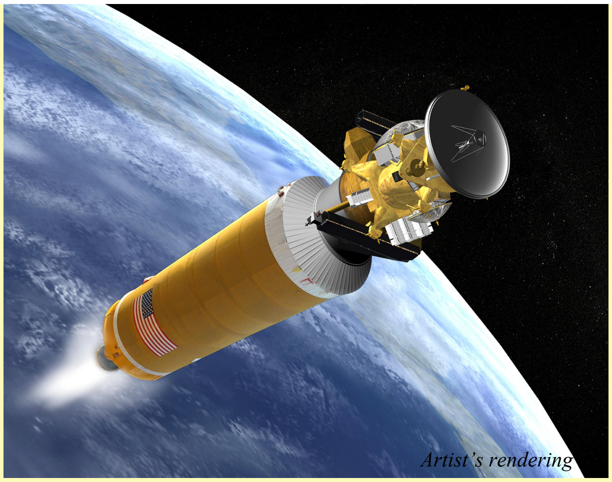
As part of broader nuclear safety considerations, TSSM would adopt ATLO, spacecraft, trajectory, and operations requirements which satisfy the nuclear safety requirements described by NPR 8715.3.

Development of coordinated launch site radiological contingency response plans for NASA launches is the responsibility of the launch site radiation safety organization. Comprehensive radiological contingency response plans, compliant with the National Response Plan and appropriate annexes, would be developed and put in place prior to launch as required by NPR 8715.2 and NPR 8715.3. The TSSM project would support the development of plans for on-orbit contingency actions to complement these ground-based response plans.

A project-specific Risk Communication Plan will be completed no later than the Mission MDR. The Risk Communication Plan will detail the rationale, proactive strategy, process and products of communicating risk aspects of the Project, including nuclear safety and plane-

tary protection. The communication strategy and process will comply with the approach and requirements outlined in the NASA Office of Space Science Risk Communication Plan for Deep Space Missions (1999) JPL D-16993 and the JPL Risk Communication Plan, 2002, JPL D-24012.

5.0 ALTERNATE LAUNCH OPPORTUNITIES



The TSSM Baseline mission takes advantage of a SEP stage with high performance NEXT ion thrusters to provide design robustness and the ability to trade flight time for mass. However, the mission feasibility does not depend on these thrusters. The TSSM mission can be accomplished with a slightly longer cruise duration using a SEP stage descoped to either flight-proven BPT-4000 Hall Thrusters or XIPS Ion Engines. In addition, a mission with the full complement of in situ vehicles is still possible without using a SEP stage at all, but at a penalty of 10.5 yr flight times to Saturn and decreased robustness to mass growth.

5.1 SEP Flight-Time Flexibility

The Baseline mission design described in §4.3 is just one point in mass/flight-time space among many similar SEP trajectories available in 2020. The use of SEP for interplanetary cruise enables freedom to trade flight time for increased delivered mass as detailed in **Figure 5.1-1**. This flexibility in the SEP trajectory design can accommodate mass growth well beyond the 33% design margin, as shown in **Figure 5.1-2**. These figures assume a 778 kg dry SEP stage, 600 kg montgolfière, and a 190 kg lander delivered as described in §4.3.

The Baseline mission design has a flight time of 9 years to Saturn, maintaining sufficient margin above the required 33% to preserve the option to fly an MMRTG-powered design. If the flight time were increased to 10.5 years, a margin of 44% on the current design could be achieved allowing an orbiter dry mass of ~2000 kg.

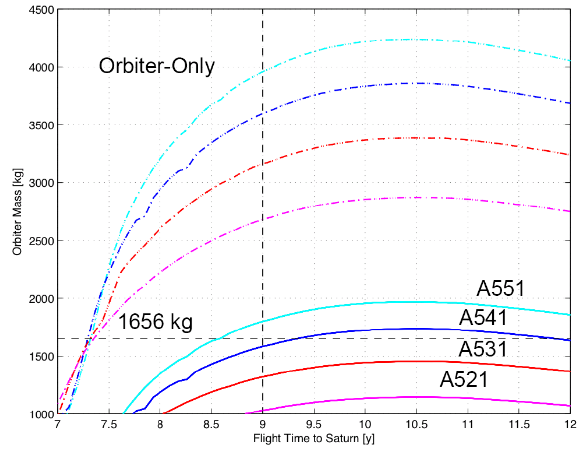


***Figure 5.1-1.** Mass and flight-time trade.*

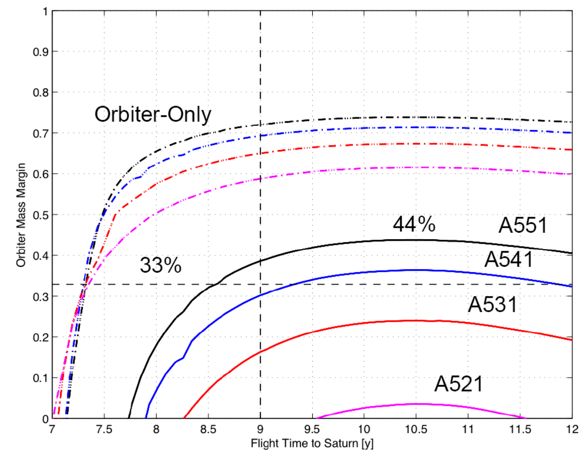


***Figure 5.1-2.** Margin and flight-time trade.*

The dashed lines at the top of these figures show the allowable orbiter dry masses if no *in situ* elements were carried. In this case, the NASA-only orbiter could reach Saturn in only 7.5 years on an Atlas V 521. This flight time could possibly be reduced even further by using a different sequence of gravity-assists.

5.2 Alternate Flight System Mission Designs

In addition to the backup trajectories that enable flying the Baseline Flight System in different launch years (discussed in §4.3.11), there are additional alternate trajectories that can complete the mission with descoped Flight System designs. Alternate launch opportunities and mission designs have been evaluated both for fallback SEP configurations as well as for chemical-propulsion-only designs.

Table 5.2-1. *2020 EVEE SEP trajectories with alternate configurations.*

Engines	Array Size [kW]	Launch Date	Arrival Date	FT to Saturn [y]	Launch C_3 [km²/s²]	Launch Mass [kg] (A551)	Xenon Prop. [kg]	Saturn V_∞ [km/s]	SOI ΔV [m/s]	Chem. Prop. [kg]
4 BPT-4000	15	9/2020	2/2030	9.4	0.9	6225	490	6.16	680	2200
3 BPT-4000	10	9/2020	12/2030	10.3	1.0	6215	631	5.75	610	2120
4 XIPS	15	9/2020	1/2030	9.3	1.0	6215	497	6.23	695	2223
3 XIPS	10	9/2020	2/2030	9.4	2.7	6035	414	6.20	690	2217

Table 5.2-2. *Alternate chemical trajectories (Atlas V 551).*

Path	Launch Date	Arrival Date	FT to Saturn [y]	Launch C_3 [km²/s²]	Launch Mass [kg]	Saturn Approach V_∞ [km/s]	DSMΔV [m/s]	SOI ΔV [m/s]	Chem. Prop. [kg]
VEME	10/2018	8/2028	9.8	16.8–18.8	4525	5.85	0	625	1834
VEE	11/2019	5/2030	10.5	15.9–17.9	4600	6.00	46	651	1930
EVEE	11/2020	5/2031	10.5	14.3–16.3	4740	5.95	131	643	2047
VEE	10/2021	3/2031	9.4	15.3–17.3	4650	6.08	47	665	1961
EVEVE	1/2022	5/2032	10.3	11.5–13.5	4980	6.23	232	693	2281

5.2.1 SEP Fallback Options

Table 5.2-1 lists 2020 EVEE trajectories that employ alternate SEP stage configurations. All of these cases can deliver the full mass for the orbiter and both *in situ* elements. The SEP stage Baseline configuration of a 15 kW array with three NEXT engines offers superior flight-time performance to these cases, but the variety of cases analyzed shows that the mission design is robust to configuration changes in the SEP stage. The electric propulsion subsystem may switch to flight proven BPT-4000 or XIPS engines at a penalty of only five months of additional flight time to Saturn. This would put the total mission duration at 13.3 years. This increase in flight time reduces the Saturn approach v-infinity and therefore the size of SOI. The fuel savings with the smaller SOI makes up for lower performance of these SEP stages relative to the Baseline design.

Although this table only shows cases in 2020 for which analyses were performed, additional cases would certainly exist in the other launch years

5.2.2 Chemical Fallback Options

Table 5.2-2 shows a set of chemical trajectories in the 2018–2022 launch years that deliver the full mass for the orbiter and both *in situ* elements. However, for these trajectories to deliver both *in situ* elements, both must be delivered at the first Titan flyby, arriving three days apart. This scenario saves ~100 m/s of mission ΔV. This reduction in ΔV combined with elimination of the 778 kg margined dry mass of the SEP stage enables the chemical trajectories to carry the full 790 kg needed for both the montgolfière and the lander. The chemical fuel load for these trajectories does not exceed the Baseline design and thus could be accommodated without modification of the baseline propellant tank design.

For these chemical propulsion missions, the flight time to Saturn would be up to 10.5 years for a 2020 launch. This would require a reduction of the Circular Orbit Phase from 20 months to 16 months in order to keep the total mission duration less than 14 years (based on stated design life of the RPS). This 16-month Circular Orbit Phase would be sufficient to provide the observations necessary to meet the mission Level 1 science requirements.

Shorter flight times would be available with Jupiter gravity-assist trajectories similar to that employed by Cassini-Huygens in 1997. However, Jupiter flybys are only available every ~19 years. For TSSM, launch opportunities that could take advantage of Jupiter gravity assists are in 2015–2017 and 2034–2036.

It should be noted that these chemical trajectories represent the maximum in the mass/flight time curves as in **Figure 5.1-1**.

These chemical trajectories are less robust to mass growth on an Atlas V 551 than the SEP designs. However, they do provide an excellent fallback option to the SEP trajectory that preserves the full complement of *in situ* elements.

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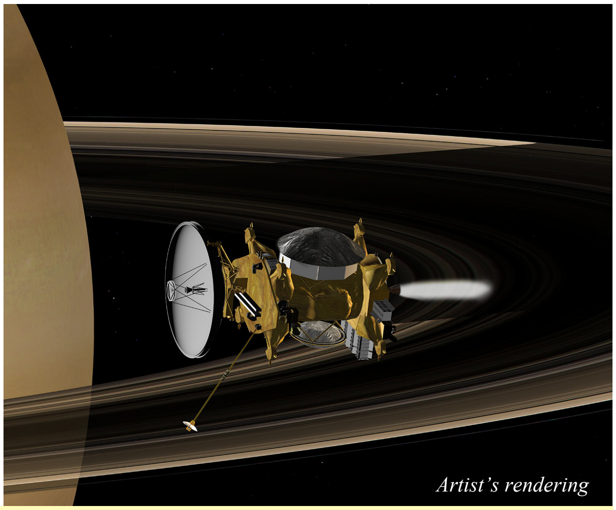
6.0 STUDY TEAM MEMBERS AND ROLES

6.1 Team Overview



*The study was conducted by two sub-teams with US and European membership that worked as a seamless integrated unit to form a focused Titan Saturn System Mission (**Figure 6.1-1**).*

The NASA/ESA-chartered Joint Science Definition Team (JSDT) focused on the science aspects, while the US and European Engineering Teams focused on the technical and programmatic aspects of the collaborative NASA/ESA mission concept. There was continuous interaction between the two teams throughout the study ensuring that the science goals and objectives were maximized within technical and programmatic constraints. A listing of the team members, their affiliations and their areas of expertise are given in **Table 6.1-1** and **Table 6.1-2**.

The JSDT held eight face-to-face meetings and one teleconference. The JSDT invited specific individuals to present at the meetings to ensure a broad input on the science objectives, potential remote sensing and *in situ* investigational methods, and measurement requirements. Instrument sub-groups were formed to define measurement capabilities that respond to measurement requirements and to define and quantify the planning payload. Mission architecture and design, system engineering, operations analysis and spacecraft members participated in each of the JSDTs to jointly resolve trades and develop operational strategies and scenarios to form a mission responsive to the science requirements.

6.2 Jet Propulsion Laboratory Role

JPL provided study leadership, task management, requirements definition, system engineering, and mission system design (flight and ground). JPL also performed the project scientist role and participated in the JSDT.

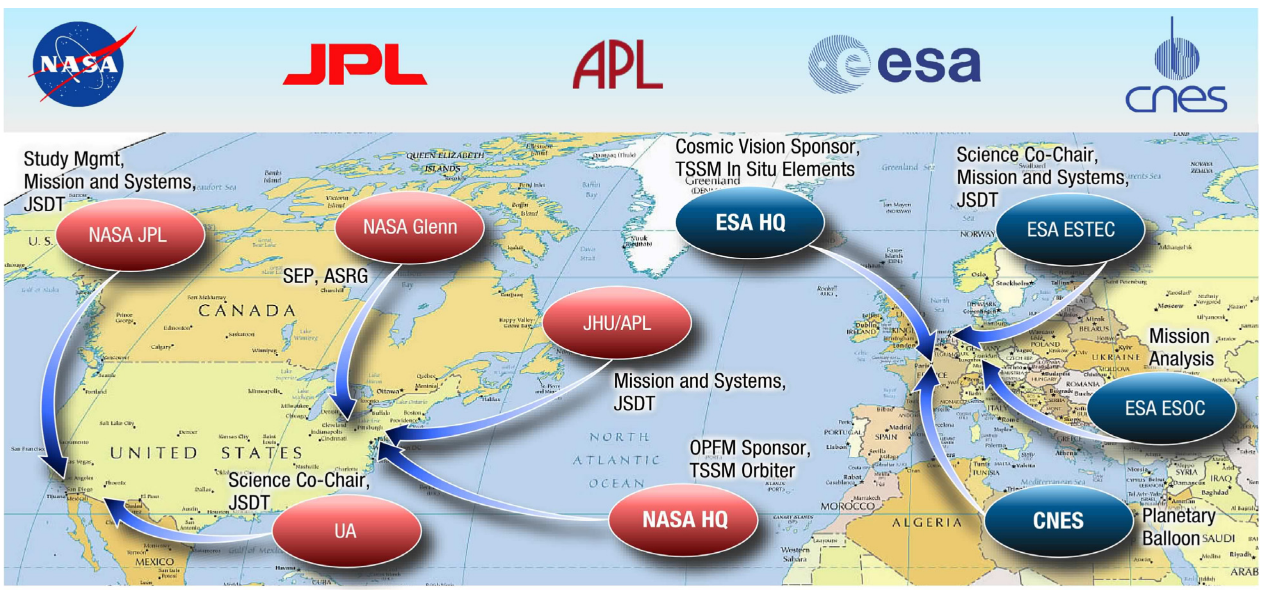


__Figure 6.1-1.__ NASA/ESA geographically diverse team operates as a seamless integrated unit incorporating lessons learned from the Cassini-Huygens model.

Table 6.1-1. *Joint science definition team.*

Member	Affiliation	Expertise
Chris McKay	Ames Research Center	Evolution of Solar System, Origins
Andy Ingersoll	Caltech	Atmospheres
Dave Stevenson	Caltech	Geophysics, Satellite Interiors
Ralf Jaumann	DLR Institute of Planetary Research, Berlin	Surfaces
Frank Sohl	DLR Institute of Planetary Research, Berlin	Interior Modeling, Geophysics
Jean-Pierre Lebreton—Co-chair	ESA	Planetary Science
Amy Simon-Miller	GSFC	Atmospheres
Ed Sittler	GSFC	Plasma Physics, Ion Mass Spectrometry
Michele Dougherty	Imperial College London	Plasma Interactions
Ingo Muller-Wodarg	Imperial College London	Plasma Interactions
Luisa Lara	Instituto de Astrofísica de Andalucía, Granada	Atmospheres, Exospheres, Exoplanets
Maria-Teresa Capria	Instituto di Astrofisica Spaziale, Rome	Enceladus, Origins
Ralph Lorenz	JHU/APL	Surfaces, Planetary Science
Elizabeth Turtle	JHU/APL	Impact Cratering, Remote Sensing
Julie Castillo-Rogez	JPL	Satellite Interiors
Candice Hansen—NASA Deputy Study Scientist	JPL	Planetary Science
Rosaly Lopes	JPL	Geology
Dennis Matson—NASA Study Scientist	JPL	Planetary Science
Christophe Sotin	JPL	Geology, Geodynamics
Olga Prieto-Ballesteros	Laboratorio de Geologia Planetaria, Madrid	Astrobiology
François Raulin	LISA Universités Paris 12 & Paris 7	Exobiology, Planetary Protection
Andrew Coates	Mullard Space Science Laboratory, Dorking	Upper Atmospheres, Enceladus
Athena Coustenis—European Lead Scientist	Observatoire de Paris-Meudon, France	Atmospheres
Ellen Stofan	Proxemy Research	Geology
Hunter Waite	Southwest Research Institute	Mass Spectrometry, Aeronomy
Paolo Tortora	Università di Bologna	Interiors, Gravity
Tetsuya Tokano	Universität zu Köln	Atmosphere Dynamics
Gabriel Tobie	Université de Nantes	Interiors
Jonathan Lunine—Co-chair	University of Arizona	Planetary Science
Jason Soderblom	University of Arizona	Planetary Surfaces
William Kurth	University of Iowa	Particles and Fields
Lorenzo Bruzzone	University of Trento	Interiors, Gravity

Table 6.1-2. *NASA technical and management team.*

Member	Affiliation	Role
Sami Asmar	JPL	RSA
Sarah Bairstow	JPL	Systems Engineering
Chuck Baker	JPL	Visualization
Pat Beauchamp	JPL	Science, Meas. Capability, Instrument Workshop
Matthew Bennett	JPL	Software
Alexis Benz	JPL	Systems Engineering
Tibor Balint	JPL	TandEM Liason
John Brophy	JPL	Solar Electric Propulsion
Kate Coburn	JPL	Enterprise Support, Secretarial
John Elliott	JPL	Flight Systems Lead, Systems Engineering
Marc Foote	JPL	TIRS
Rob Green	JPL	HiRIS
Troy Goodson	JPL	Navigation/Flight Path Control
Dave Hansen	JPL	Telecommunication
Denise Hollert	JPL	Mechanical/Structure/Mechanisms

Member	Affiliation	Role
Sarah Hornbeck	JPL	Systems Engineering
John Hunter	JPL	Programmatics
Melissa Jones	JPL	Systems Engineering
Insoo Jun	JPL	Radiation Environment and Performance
Ken Klaasen	JPL	Instrument Engineering, Measurement Capability
Ira Katz	JPL	Solar Electric Propulsion
Milana Kozulina	JPL	Cost Lead
Try Lam	JPL	SEP Trajectory
Damon Landau	JPL	SEP Trajectory / Chemical Trajectory
Joe Lewis	JPL	Propulsion Tanks
Sima Lisman	JPL	Attitude Control and Articulations
Rob Lock	JPL	Mission Planning, Concept of Ops, Scenarios
Daniel Lyons	JPL	Aerobraking
Carolina Maldonado	JPL	Command and Data Handling
Tim McElrath	JPL	Navigation/Orbit Determination
Peter Meakin	JPL	Attitude Control and Articulations
Imran Mehdi	JPL	SMS
Ricardo Mendoza	JPL	Telecommunications
Anthony Mittskus	JPL	Telecommunications
Bob Miyake	JPL	Thermal
David Mohr	JPL	Mission Planning, Concept of Ops, Scenarios
Barry Nakazono	JPL	Propulsion
Pablo Narvaez	JPL	EMI/EMC
Bill Nesmith	JPL	RPS
Don Nieraeth	JPL	Solar Electric Propulsion PPU Costing
Brian Okerlund	JPL	Mechanical Configuration, CAD
Joon Park	JPL	Artist
Fred Pelletier	JPL	Navigation/Orbit Determination
Anastassios Petropoulos	JPL	SEP Trajectory
Christina Poon	JPL	Technical Editing
Tom Randolph	JPL	BPT-4000 Hall Thruster
Kim Reh—Study Lead	JPL	Project Management and Systems Engineering
Ali Safaeinili	JPL	TiPRA
Carl Sauer	JPL	SEP Trajectory
Joseph Smith	JPL	Ground Systems Engineering
Bill Smythe	JPL	HiRIS, Measurement Capability
Steve Snyder	JPL	NEXT Thruster
Tom Spilker	JPL	Mission Architect, Science Accommodation
Andy Spry	JPL	Planetary Protection
Nathan Strange	JPL	Mission Architecture and Design
Violet Tissot	JPL	Schedules
Valerie Thomas	JPL	Mission Assurance
Paul Timmerman	JPL	Power
Arv Vaisnys	JPL	Telecommunications
Tracy Van Houten	JPL	Systems Engineering
Chen-Wan Yen	JPL	Chemical Trajectory
Corby Waste	JPL	Artist
Greg Welz	JPL	Msn Operations and Ground Data Systems Lead
Jose Guzman	JHU/APL	Titan Orbit
Ted Hartka	JHU/APL	Mechanical/Structure/Mechanisms

Member	Affiliation	Role
Ken Hibbard	JHU/APL	Systems Engineering
Mark Holdridge	JHU/APL	Operations and Lessons Learned
James Leary	JHU/APL	Systems Engineering
Tom Magner	JHU/APL	Project Management and Systems Engineering
Margaret Morris	JHU/APL	Technical Editing
Michael Paul	JHU/APL	Systems Engineering, Risk Assessment
Mark Perry	JHU/APL	Payload System Engineering Lead
Steve Thibault	JHU/APL	Project Systems Integration and Test Lead
Steve Vernon	JHU/APL	RPS Integration
Dave Weir	JHU/APL	Payload Layout
Scott Benson	NASA Glenn	Solar Electric Propulsion
Tibor Kremic	NASA Glenn	Solar Electric Propulsion
Paul Schmitz	NASA Glenn	ASRG/RPS
Richard Shaltens	NASA Glenn	ASRG/RPS
John Brasunas	GSFC	TIRS
Emmanuel Lellouch	Observatoire de Paris-Meudon, France	SMS
Roger Yelle	University of Arizona	Titan Atmospheric Modeling

6.3 University of Arizona Role

The University of Arizona performed the role as JSDT co-Lead and participated on the JSDT.

6.4 Johns Hopkins University-Applied Physics Laboratory Role

APL participated in the JSDT and mission system engineering. APL implemented the lead roles for Requirements analysis, Project Risk Assessment, Payload System Engineering, *in situ* accommodation, Project System Integration and Test and Phase E lessons learned. APL also provided independent assessment of the design concepts.

6.5 National Aeronautics and Space Administration Role

NASA sponsored the Outer Planet Flagship Mission (OPFM) studies, provided direction and carried out interim reviews. NASA also conducted an independent Science, Technical, Management and Cost review of the TSSM study concept.

6.6 European Space Agency Role

ESA sponsored the Outer Planet portion of Cosmic Vision activities in partnership with the NASA sponsored OPFM studies. Jean-Pierre Lebreton, ESA-ESTEC (European Space Research and Technology Centre), participated as co-Chair of the TSSM JSDT. Many ESA member state scientists from across Europe participated on the JSDT as indicated in **Table 6.1-1**. They contributed to all aspects related to the *in situ* elements as well as the overall mission definition. Christian Erd led the ESA-ESTEC conceptual design of the *in situ* mission and its elements. ESA-ESOC (European Space Operations Centre) provided mission analysis for Entry, Descent and Landing and Entry, Descent and Inflation for the lake lander and montgolfière respectively. He and his team worked as integrated members of the joint study team to develop a well integrated NASA/ESA collaborative mission.

6.7 Centre National d'Etudes Spatiales Role

CNES provided the balloon envelope and deployment system design for the ESA-ESTEC montgolfière conceptual design. Jean-Marc Charbonnier led the CNES team and worked closely with ESA and JPL aerial vehicle experts to establish a common approach for the TSSM montgolfiére concept. CNES provided a substantial financial and technical commitment for the development of relevant balloon technologies and the project's flight unit (see letter of support from CNES, Appendix M).

6.8 NASA Glenn Role

NASA Glenn supported the evaluation of Solar Electric Propulsion (SEP) options during the mission architectural assessment phase and provided input for SEP stage design. NASA Glenn personnel also provided technical information for integration of ASRGs into the

orbiter conceptual design (see letter of support from NASA Glenn, Appendix M).

6.9 APL-JPL Outer Planets Steering Group

The Study Team interacted with and was advised by a steering group consisting of the following people:

- Chris Jones: JPL, Director for Solar System Exploration Co-Chair
- John Sommerer: APL, Space Department Head Co-Chair
- John Casani: JPL, Special Assistant to the Director
- Andy Cheng: APL, Chief Scientists, Space Department
- Jim Cutts: JPL, Program Manager, Outer Planet Flagship Mission Studies
- Walt Faulconer: APL, Civilian Space Business Area Executive
- Rick Grammier: JPL, Deputy Director for Solar System Exploration
- Torrence Johnson: JPL, Chief Scientist, Solar System Exploration Directorate
- Ted Mueller: APL, Civilian Space Program Area Manager
- Cheryl Reed: APL, Civilian Space Program Development Manager

6.10 Study Results Review Process

Elements of this concept study report have been reviewed extensively by independent sets of discipline specialists and by APL/JPL management as follows:

1. The team has gained the support of the NASA PPO for the PP approach concept (Conley 2008).
2. The Science Goals and Objectives were subjected to a review at various science meetings by independent planetary scientists.
3. The Science Goals and Objectives and the mission concept were presented at the Outer Planets Assessment Group (OPAG) meeting in April 2008.
4. The mission concept and approach was subjected to two NASA HQ interim reviews in April and June of 2008.
5. Subsystems were subjected to focused internal reviews by JPL and APL personnel for technical validity, including detailed comparison and contrasting with other flight proven subsystems.
6. The mission concept, measurement requirements, planning payload, science operational scenario, and overall approach was presented to the broad science and technical community through the conduct of an Instrument Workshop in June of 2008 and various conferences, symposiums, and workshops to communicate results and solicit external feedback.
7. The mission implementation has been reviewed by technical, management, and cost review boards and line management organizations internal to JPL and APL. This resulted in a very thorough assessment of study results that produced 460 review item discrepancies (RIDs), all of which have been responded to in finalizing the TSSM study report.
8. Finally, the overall concept study report was reviewed by both JPL and APL management prior to submission to NASA for independent review.

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A. ACRONYMS AND ABBREVIATIONS

ACE	Attitude Control Engineer
ACS	Attitude Control Subsystem; *also* Attitude Control System
ACT	Applied Coherent Technology [Corporation]
A/D	Analog-to-Digital
AD	Attitude Determination
AO	Announcement of Opportunity
APL	Applied Physics Laboratory
APML	Approved Parts and Materials List
ARC	Ames Research Center
ARTG	Advanced Radioisotope Thermoelectric Generator
ASAT	Aerocapture System Analysis Team
ASI	Italian Space Agency
ASI/MET	Atmospheric Structure Instrument/Meteorological Package
ASIC	Application-Specific Integrated Circuit
ASRG	Advanced Stirling Radioisotope Generator
ATLO	Assembly, Test and Launch Operations
BB	Breadboard
BIS	Balloon Imaging Spectrometer
BoE	Basis of Estimate
BOL	Beginning of Life
BOM	Beginning of Mission
BTM	Balloon Targeting Maneuver
BU	Backup
BWG	Beam Waveguide
C&DH	Command and Data Handling
C&T	Command and Telemetry
CADRe	Cost Analysis Data Requirements
CAPS	Cassini Plasm Spectrometer
CBE	Current Best Estimate
CC	Custom Card
CCSDS	Consultative Committee for Space Data Systems
CDA	Cosmic Dust Analyzer
CDR	Critical Design Review
CE	Compute Element
CEP	Critical Event Planner
CEPCU	Compute Element Power Converter Unit
CER	Cost Estimating Relationship
CEV	Crew Exploration Vehicle
CFDP	CCSDS File Delivery Protocol
CG	Center of Gravity
CIMS	Cassini Information Management System
CIRS	Cassini Infrared Spectrometer
CM	Configuration Management
CMMI	Capability Maturity Model Integration
CNES	Centre National d'Études Spatiales
CNSA	China National Space Administration
CoM	Center of Mass
CONTOUR	Comet Nucleus Tour
COPV	Composite Overwrapped Pressure Vessels
COSPAR	Committee on Space Research
COTS	Commercial Off-the-Self
Cp	Center of Pressure
CPHP	Capillary Pumped Heat Pipe
CPTi	Commercially Pure Titanium
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
CRS	Cost Risk Subfactors
CSA	Canadian Space Agency
CSC	Computer Software Component
CSM	Cassini Solstice Mission
CTM	Contract Technical Manager
CTX	Context Imager
CV	Cosmic Vision
CY	Calendar Year
D/H	Deuterium/Hydrogen
DC	Direct Current
DCIU	Digital Control and Interface Unit
DDOR	Delta-Differential One-way Range

DHMR	Dry Heat Microbial Reduction
DISR	Descent Imager/Spectral Radiometer
DLR	German Aerospace Center
DMOM	Deputy Mission Operations Manager
DoD	Department of Defense
DOD	Depth of Discharge
DOE	Department of Energy
DoF	Degree-of-Freedom
DPA	Destructive Physical Analysis
DPMR	Deputy Project Manager for Radiation
DPP	Design Principles and Practices
DPSER	Deputy Project System Engineer for Radiation
DPU	Data Processing Unit
DSA	DSMS Service Agreement
DSM	Deep Space Maneuver
DSMS	Deep Space Mission System
DSN	Deep Space Network
DTE	Direct to Earth
DTM	Developmental Test Model
E/PO	Education and Public Outreach
E/Q	Mass/charge
EACs	Estimates at Completion
EAR	Export Administration Regulation
ECU	Electronics Control Units
EDD	Entry, Descent, and Deployment
EDI	Entry, Descent, and Inflation
EDL	Entry, Descent, and Landing
EDR	Experiment Data Records
EEE	Electrical, Electronic, and Electromechanical
EEIS	End-to-End Information System
EELV	Evolved Expandable Launch Vehicle
EIS	Environmental Impact Statement
EM	Engineering Model
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
ENA	Energetic Neutral Atoms
EOM	End of Mission
EPA	Environmental Protection Agency
EPINS	Electronic Parts Information System
EPS	Electrical Power System
EPSA	Electrical Part Stress Analysis
ERD	Environmental Requirements Document
ESA	European Space Agency
ESMD	Exploration Systems Mission Directorate
ESOC	European Space Operations Centre
ESTEC	European Space Research and Technology Centre
EU	European Union
EUV	Extreme Ultraviolet
EVEE	Earth-Venus-Earth-Earth
EVEEGA	Earth-Venus-Earth-Earth Gravity Assist
EVM	Earned Value Management
F&P	Fields and Particles
FC	Flight Controller
FCD	Flow Control Device
FDU	Fault Detection Unit
FEM	Finite Element Model
FET	Field Effect Transistor
FIPS	Fast Imaging Plasma Spectrometer
FIR	Far Infrared
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
FO	Foldout
FOV	Field of View
FPGA	Field Programmable Gate Array
FPP	Flight Project Practices
FRISK	Formal Risk [Analysis]
FSM	Flight System Manager
FSTB	Flight System Testbed
FSW	Flight Software

FSWTB	Flight Software Testbed
FT	Flight Time
FTE	Full Time Equivalent
FTIR	Fourier Transform Infrared
FTS	Fourier Transform Spectrometer
FY	Fiscal Year
GBCO	Gadolinium Barium Copper Oxide
G&C	Guidance and Control
GCM	Global Circulation Model
GCMS	Gas Chromatograph Mass Spectrometer
GDE	Gimbal Drive Electronics
GDS	Ground Data System
GNC	Guidance, Navigation and Control
GOTS	Government Off-the-Shelf
GPHS	General Purpose Heat Source
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
H/W	Hardware
HF	High Frequency
HGA	High Gain Antenna
HiRIS	High-Resolution Imager and Spectrometer
HiRISE	High-Resolution Imaging Science Experiment
HPCU	Housekeeping Power Converter Unit
HQA	Hardware Quality Assurance
HR	High Resolution
HRCR	Hardware Requirements Certification Review
HST	Hubble Space Telescope
HVDC	High-Voltage Down-Converter
HVEA	High Voltage Electronics Assembly
HVPA	High-Voltage Power Assembly
I&T	Integration and Test
I/O	Input/Output
IAU	International Astronomical Union
IC	Internal Charging
ICC	Instrument Command Channel
ICD	Interface Control Documents
ICDR	Instrument Concept Design Reviews
ICE	Independent Cost Estimate
IDS	Interdisciplinary Scientists
IFOV	Instantaneous Field-of-View
IKI	Russian Space Research Institute
IMC	Image Motion Compensation
IMS	Ion Mass Spectrometer
IMU	Inertial Measurement Unit
INMS	Ion Neutral Mass Spectrometer
INSRP	Interagency Nuclear Safety Review Panel
IO	Instrument Operations
IONet	Internet [Protocol] Operational Network
IPS	Ion Propulsion System
IR	Infrared
IRIS	Infrared Interferometer Spectrometer
IRO	Indian Space Research Organization
IRS	Infrared Spectrometer
IRU	Inertial Reference Unit
ISE	*In Situ* Element
ISI	Integral Systems Inc.
ISO	International Standards Organization; *also* Infrared Space Observatory
I_{sp}	Specific Impulse
ISS	Imaging Science Subsystem
ITAR	International Traffic in Arms Regulations
ITC	Integration and Test Complexity
IV&V	Independent Verification and Validation
JAXA	Japanese Aerospace Exploration Agency
JDST	Joint Science Definition Team
JEDI	Juno Energetic-Particle Detector Instrument
JGA	Jupiter Gravity Assist

JHU-APL	Johns Hopkins University Applied Physics Laboratory
JPL	Jet Propulsion Laboratory
JSDT	Joint Science Definition Team
JSO	Jupiter System Observer
JURAP	Joint Users Review Allocation Planning
KDP	Key Decision Point
KM	Knowledge Management
KSC	Kennedy Space Center
LA	Launch Approval
LAE	Launch Approval Engineering
LEF	Linear Electric Field
LEMMS	Low Energy Magnetospheric Measurement System
LGA	Low Gain Antenna
LL	Lessons Learned
LMSS	Lockheed Martin Space Systems [Company]
LORRI	Long Range Reconnaissance Imager
LR	Low Resolution
LSA	Lighting Suppression Assembly
LST	Local Solar Time
LTM	Landing Targeting Maneuver
LV	Launch Vehicle
LVA	Launch Vehicle Adapter
LVC	Launch Vehicle Contingency
LVDS	Low Voltage Differential Signaling
MA	Mission Assurance
MAG	Magnetometer
MAM	Mission Assurance Manager
MAPP	Magnetometer and Plasma Package
MARCI	Mars Color Imager
MARSIS	Mars Advanced Radar for Subsurface and Ionosphere Sounding
MBTOF	Multiple Bounce Time-of-Flight
MCP	Micro-channel Plate
MCR	Mission Concept Review
MCS	Mars Climate Sounder
MDR	Mission Definition Review
MEL	Mass Equipment List
MER	Mars Exploration Rover
MESSENGER	Mercury Surface, Space Environment, Geochemistry, and Ranging
MEV	Maximum Expected Value
MGA	Medium Gain Antenna
MGS	Mars Global Surveyor
MGSS	Multi-mission Ground Support System
MI	Microscopic Imager
MIMI	Magnetospheric Imaging Instrument
MIMU	Magnetospheric Imaging Instrument
MIPF	Multi-mission Image Processing Facility
MIR	Mid Infrared
MIRO	Microwave Instrument for the Rosetta Orbiter
MIT	Minimum Impulse Thruster
MLI	Multilayer Insulation
MLS	Microwave Limb Sounder
MMR	Monthly Management Review
MMRTG	Multimission Radioisotope Thermoelectric Generator
MO&GDS	Mission Operations and Ground Data Systems
MOA	Memorandum of Agreement
MOC	Mars Observer Camera
MOI	Mercury Orbit Insertion
MOM	Mission Operations Manager
MOPS	Mission Operations
MOS	Mission Operations System
MOST	Microvariability and Oscillation of Stars
MOU	Memorandum of Understanding
MRB	Materials Review Board
MRD	Mission Requirements Document
MREU	MSAP Remote Engineering Unit
MRO	Mars Reconnaissance Orbiter

MSAP	Multimission System Architecture Platform
MSGR	MESSENGER
MSIA	MSAP System Interface Assembly
MSL	Mars Science Laboratory
MSS	Mission Support & Services
MST	Mission Scenario Test
MSTB	Mission System Testbed
MTIF	MSAP Telecom Interface
NAFCOM	NASA/Air Force Cost Model
NAIF	Navigation Ancillary Information Facility
NASA	National Aeronautics Space Administration
NEAR	Near Earth Asteroid Rendezvous
NEOSSat	Near Earth Object Surveillance Satellite
NEPA	National Environmental Policy Act
NEXT	NASA’s Evolutionary Xenon Thruster
NH	New Horizons
NHOPS	New Horizons Hardware-in-the-Loop Simulator
NICM	NASA Instrument Cost Model
NIR	Near Infrared
NMO	NASA Management Office
NPG	NASA Procedures and Guidelines
NPR	NASA Procedural Requirements
NSC	National Security Council
NSPAR	Non-Standard Parts Approval Request
NSTAR	NASA Solar Electric Propulsion Technology Application Readiness
OD	Orbit Determination
ODM	Orbiter Deflection Maneuver
OPAG	Outer Planets Assessment Group
OPFM	Outer Planet Flagship Mission
ORS	Optical Remote Sensing
ORT	Operational Readiness Test
OSS	Outer Solar System
OSTP	Office of Science and Technology Policy
OTM	Orbit Trim Maneuvers
P/L	Payload
PA	Power Assembly
PAB	Project Advisory Board
PD	Presidential Directive
PDR	Preliminary Design Review
PDS	Planetary Data System
PDU	Power Distribution Unit
PEL	Power Equipment List
PEPE	Plasma Experiment for Planetary Exploration
PEPSSI	Pluto Energetic Particle Spectrometer Sciences Investigation
PET	Proton/Electron Telescope
PF/R	Problem/Failure Reports
PFM	Proto-Flight Models
PFS	Planetary Fourier Spectrometer
PHSF	Payload Hazardous Servicing Facility
PI	Principal Investigator
PIND	Particle Impact Noise Detection
PIP	Project Information Package
PM	Project Manager
PMA	Pressure Management Assembly
PMS	Polymer Mass Spectrometer
PMSR	Preliminary Mission System Review
POM	Payload Operations Manager
POP	Program Operating Plan
PP	Planetary Protection
PPF	Payload Processing Facility
PPI	Particle and Plasma Instrument
PPO	Planetary Protection Office
PPU	Power Processing Unit
PRM	Periapsis Raise Maneuver
PRS	Problem Reporting System
PRT	Platinum Resistor Thermometers

PS	Project Scientist
PSC	Polar Stratospheric Cloud
PSCG	Project Science Coordination Group
PSE	Project Systems Engineer
PSLA	Project Support Level Agreement
PSO	Primary Science Orbit
PSP	Primary Science Phase
PSRD	Project System Requirements Document
PSSG	Project Science Steering Group
PWM	Pulse Width Modulated
RADAR	Radio Detection and Ranging
RadE	Radiation Environment
RadPSM	Radiation Parts, Sensors, and Materials
RAM	Responsibility Assignment Matrix
RARB	Resource Allocation Review Board
RCS	Reaction Control System
RDE	Realtime Development Environment
RDF	Required Design Factor
REP	Radioisotope Electric Propulsion
REX	Radio Science Experiment
RF	Radio Frequency
RFA	Requests for Actions
RGA	Residual Gas Analysis
RHU	Radioisotope Heater Unit
RLAT	Radiation Lot Acceptance Testing
ROD	Record of Decision
ROM	Rough Order-of-Magnitude
ROSINA	Rosetta Orbiter Spectrometer for Ion and Neutral Analysis
RPS	Radioisotope Power System
RPWS	Radio and Plasma Wave
RS	Radio Science; *also* Remote Sensing
RSA	Radio Science and Accelerometer
RSB	Remote Serial Bus
RSS	Radio Science Subsystem
RTG	Radioisotope Thermoelectric Generator
RTOF	Reflection Time of Flight
RWA	Reaction Wheel Assembly
RY	Real Year
S&M	Structures and Mechanisms
S/C	Spacecraft
SAMPEX	Solar, Anomalous, Magnetospheric Particle Explorer
SAR	Safety Analysis Report
SATRAD	Saturn Radiation Science
SCO	Spacecraft Operations
SDC	Student Dust Counter
SDRAM	Synchronous Dynamic Random Access Memory
SDT	Science Definition Team
SEE	Single-Event Effects
SEEA	Single Event Effects Analysis
SEP	Solar Electric Propulsion
SEQADAPT	Sequence Adaptor
SEQGEN	Sequence Generation
SER	Safety Evaluation Report
SFC	Spacecraft Flight Computer
SHARAD	Shallow (subsurface) Radar
SIR	System Integration Review
SIRU	Space Inertial Reference Unit
SIU	SEP Interface Unit
SLT	Saturn Local Time
SMA	Safety and Mission Assurance
SMC	System Memory Card
SMD	Science Mission Directorate
SMS	Sub-Millimeter Sounder
SNR	Signal-to-Noise Ratio
SOC	Science Operations Center
SOHO	Solar and Heliospheric Observatory
SOI	Saturn Orbit Insertion
SP	Science Planning
SPF	Single-Point Failure
SPICE	Spacecraft, Planet, Instrument, C-matrix, Events

SPP	Surface Properties Package
SQA	Subcontractor's Quality Assurance
SRAM	Static Random Access Memory
SRU	Stellar Reference Unit
SS	Subsystem
SSA	Sun Sensor Assemblies
SSE	Solar System Exploration
SSR	Solid State Recorder
ST5	Space Technology 5
STATESIM	State Simulator
STEREO	Solar Terrestrial Relations Observatory
STM	Systems Trade Model
SWAP	Solar Winds and Plasma (spectrometer)
SWAS	Sub-millimeter Wave Astronomy Satellite
SWRI	Southwest Research Institute
SWS	Short-Wavelength Spectrometer
T&C	Telemetry and Command
TAA	Technical Assistance Agreement
TCM	Trajectory Correction Maneuvers
TDC	Time to Digital Converter
TE	Titan Explorer
TEEP	Titan Electronic Environment Package
TEMPEST	Titan Exploration and Mapping Plus Enceladus and Saturn Tour
TES	Thermal Emission Spectrometer
TGA	Thruster-Gimbal Assemblies
TID	Total Ionizing Dose
TiPEx	Titan Prebiotic Explorer
TiPI	Titan Probe Imager
TiPRA	Titan Penetrating Radar and Altimeter
TIRS	Thermal IR Spectrometer
TLCA	Titan Lander Chemical Analyzer
TMC	Technical, Management and Cost
TMCA	Titan Montgolfière Chemical Analyzer
TO	Titan Orbiter
TOES	Titan Organic Exploration Study
TOF	Time of Flight
TOI	Titan Orbit Insertion
TRL	Test Readiness Level
TRS	Titan Radar Sounder
TSSM	Titan and Saturn System Mission
TTL	Transistor Transistor Logic
TVC	Thrust Vector Control
TWTA	Traveling Wave Tube Amplifier
UART	Universal Asynchronous Receiver/Transmitter
UHF	Ultra High Frequency
ULO	Uplink Operations
USO	Ultra-Stable Oscillator
UST	Universal Space Transponders
UV	Ultraviolet
UVIS	Ultraviolet Imaging Spectrograph
V	Voltage
V&V	Verification and Validation
VEEGA	Venus-Earth-Earth Gravity Assist
VEGA	Venus-Earth Gravity Assist
VIMS	Visual and Infrared Mapping Spectrometer
VISTA-B	Visual Imaging System Titan for Balloon
WBS	Work Breakdown Structure
WCA	Worst Case Analysis
WSTB	Workstation Testbed
XFC	Xenon Flow Control
XFS	Xenon Feed System
XIPS	Xenon-Ion Propulsion
YBCO	Yttrium Barium Copper Oxide

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C. TELECOMMUNICATIONS LINK ANALYSIS

C.1 Introduction

This appendix contains the performance estimates for the TSSM telecommunication links. The telecommunications subsystem is described in §4.4. The following paragraphs detail the assumptions that went into the link analysis, as well as presenting results of the analysis with charts and link design control tables where appropriate.

C.2 Requirements

The link shall provide for Command, Telemetry, and Radiometric Navigation:

Radiometric Navigation Performance

1. Doppler: < 0.1 mm/sec in 60 sec
2. Ranging: 4 m in 10 min
3. ΔDOR (VLBI): 0.12 ns

Command Performance at BER < 1E-5

1. Minimum rate: 7.8 bps
2. Maximum rate: 2000 bps

Engineering & Science Telemetry Performance BER < 1E-6

1. Minimum rate: 10 bps
2. Maximum rate: ~140 kbps at SOI +6 mo

Key Functions

1. Initial Acquisition
2. Safemode Telecom & Command
3. Critical Event Data & Monitoring
4. Single fault immunity
5. Communications relay for *in situ* elements

C.3 Telecommunications Subsystem Overview

The maximum range is 10.1 AU for the Titan science phase.

In order to minimize transmit circuit losses, the telecom hardware is mounted on the back of the HGA which reduces the loss between the output of the high-power amplifiers and the 4 m, X/Ka-band HGA.

Flight system downlink communication is primarily via Ka-band, with X-band used for all uplink commanding, inner cruise and safemode communication. Dual string, cross-strapped USTs with 25 W X-band TWTAs and 35 W Ka-band TWTAs provide X-up/X-down, Ka-up/Ka-down and X-up/Ka-down for commanding, data return, navigation and radio science. The Ka-band link can only be operated with the HGA, but the X-band link can be operated with the HGA, MGA, or either LGA. Data rates achievable for the inner cruise portion of the trajectory using the MGA and LGA are shown in **Figure C.3-1**.

The high rate links are designed to communicate to DSN 34 m BWG antennas. Link performance for cruise and Saturn system tour does not constrain the design. The MGA link example is for safe modes during the Titan

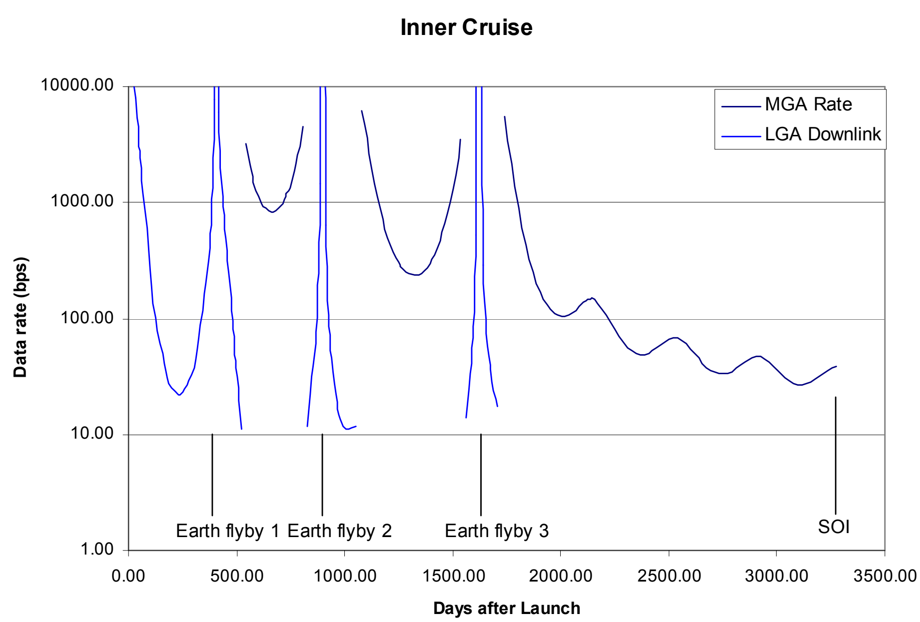


Figure C.3-1. *TSSM Inner Cruise Data Rates*

science phase to a 34 m array. The MGA 13 deg ½ angle is larger than the Titan SPE angle of ~7°. The 10 bps rate shows excess margin above the required 3 dB design margin.

C.4 Assumptions

Table C.4-1 lists mission and telecom parameters used in the link analyses presented in this Appendix.

Table C.4-1. *Telecom link analysis assumptions.*

Parameter	X-Band Value	Ka-Band Value	Parameter	X-Band Value	Ka-Band Value
Maximum S/C Distance (AU)	10.5	10.5	S/C Transmitting Power (Watts)	25	35
Uplink Transmitter Power (W)	20,000	800	Downlink Modulation Format Name(s)	PCM/PSK/PM	PCM/PSK/PM
Uplink Command Mod Index (Rad)	0.94 - 1.5	-	Downlink Frequency Band (GHz)	8.425	32.05
Uplink Ranging Mod Index (Rad)	1.1	1.1	S/C Downlink Telemetry Mod Index (Rad)	0.7 - 1.3	1.3
Uplink Frequency Band (GHz)	7.17	34.33	S/C Downlink Ranging Mod Index (Rad)	0.3	0.3
Uplink Transmit Antenna Gain (dBi)	DSS-25, 67.0	DSS-25, 79.5	S/C HGA Transmit Gain (dBi) / Loss (dB)	48.4/1.0	60.7/1.0
S/C HGA Receive Gain (dBi) / Loss (dB)	47.0/2.2	61.3/2.5	S/C MGA Transmit Gain (dBi) / Loss (dB)	22.0/2.0	-
S/C MGA Receive Gain (dBi) / Loss (dB)	21.5/2.5	-	S/C LGA Transmit Gain (dBi) / Loss (dB)	9.0/2.0	-
S/C LGA Receive Gain (dBi) / Loss (dB)	8.7/2.5	-	Downlink Receive Antenna Gain (dBi)	DSS-25, 68.4	DSS-25, 79.0
Telecommand Data Rates (b/s)	2000/7.8	-	Telemetry & Science Data Rates (b/s)	10 - 1000	50,000 - 200,000
Telecommand Bit-Error-Rate	1.00E-05	-	Telemetry Coding (Name)	Turbo 1/3	Turbo 1/6
S/C Receiver Noise Temperature (K)	400	500	Telemetry Frame Length	1784 and 8920	8920
S/C Receiver Bandwidth (Hz)	20	20	Frame Error Rate	1.00E-04	1.00E-04
Turnaround Ranging (Y/N)	Y	Y	Required Ranging Accuracy (m)	10	10

C.5 Link Design Control Tables

The link Design Control Tables (DCT) were derived from the telecom concept and design assumptions. Because the detailed design has not yet been determined, some parameters, such as circuit losses, were assumed based on actual designs from previous projects. In this case, parameter assumptions were derived from the MRO Telecom design, which has a very similar design concept, configuration and operations scenario.

DSN performance parameters were derived from the DSN Telecommunications Link Design handbook (DSN 810-005, Rev. E) which have been programmed into the Excel based link budget design tool v5.2a maintained by JPL's Flight Communications Systems section.

Nominal Ka band Science Return DCT

Table C.5-1 shows the link performance for the nominal science return link for the Saturn/Titan tour phase of the mission. At worst case distance ~10 AU, the 34 m BWG subnet will be capable of supporting links at 140 kbps with 3 dB of margin. The data rate performance will increase as the distance between Saturn and Earth decreases.

Sun Safe Orientation DCT

In the event of the safing of the TSSM spacecraft, the attitude control subsystem will use HGA mounted sun trackers to orient the MGA toward the sun. **Table C.5-2** shows the MGA will provide sufficient link margin to support 20 bps at X-band to a pair of arrayed 34 m antennas.

Uplink Command Performance DCT

Table C.5-3 shows upwards of 13 dB of performance margin for an uplink data rate of 2000 bps from a 34 m BWG at X-band.

SOI Orientation—LGA Carrier Only

Table C.5-4 shows a 70 m or equivalent aperture in combination with the open loop radio science receivers will be necessary to track the spacecraft during the SOI burn. It is assumed that similar to Cassini, the TSSM project will track the spacecraft during the SOI burn using the RSRs. In 2004 the RSRs were used to track the signal from Cassini down to 3.5 dB/Hz. A 70 m or equivalent will provide ~9 dB/Hz CNR for the SOI burn via the LGA.

In Situ Links

The TSSM *in situ* relay links were modeled using information provided by ESA for their telecom systems. The montgolfière includes a 25 W X-band transmitter using a 0.5 m steerable high gain antenna. The lander has an 8 W transmitter, also in X-band, transmitting through a low gain omni antenna. **Tables C.5-5** and **C.5-6** present link analyses for the montgolfière and the lander respectively, at their maximum ranges from the orbiter. The range for the *in situ* links varies significantly over time; **Figure C.5-1** illustrates the data rate achievable over these links as a function of range.

Table C.5-1. 35 W Ka-band TWTA, 4 m HGA, 34 m DSN, Turbo 1/6, 0.7 mrad pointing.

D. Hansen

Titan Downlink Design Control Table

run date: 28-Aug-2008
dct version v5.1d

35.0 W TWTA

Ka-Band HGA, 4 m antenna diameter, 0.04° off-point
DSN 34 m station /Configuration: X/Ka, Diplex RCP
Goldstone/20 deg. elevation/90% CD Weather (Year Average)
Hot body noise = 0 K
2-way coherent
Tlm channel/ (Turbo 1/6, 8920 bit frame)/ FER=10^-4

Carrier Loop Bandwidth = 10.0 Hz
Symbol Rate to the SDST= 840000 sps
Data Bit Rate Before All Encoding= 140000 bps

1.496E+09	Range, km
10.0000	Range, AU
1.39	OWLT, hrs
20.00	SEP, deg
20	Elev. Angle, deg

	Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var	S	Ka	RF band
									32050	Freq, MHz
	TRANSMITTER PARAMETERS									
1	S/C RF Power Output	dBm	45.44	0.30	0.00	45.54	0.0050	T	35.0	Xmtr Pwr, W (EOL)
2	Total Circuit Loss	dB	-1.00	0.40	-0.40	-1.00	0.0535	U		
3	Antenna Gain (on boresight)	dBi	60.71	0.50	-0.50	60.71	0.0417	T	0.16	3 dB Beamwidth
4	Ant Pointing Loss	dB	-0.97	0.60	-0.60	-0.97	0.1192	U	HGA	S/C Antenna
5	EIRP (1+2+3+4)	dBm				104.28	0.2194			
	PATH PARAMETERS									
6	Space Loss	dB	-306.06	0.00	0.00	-306.06	0.0000	D		
7	Atmospheric Attn	dB	-0.71	0.00	0.00	-0.71	0.0000	D	90	Weather %
									Year Average	Distribution Type
	RECEIVER PARAMETERS									
8	DSN Antenna Gain	dBi	78.52	0.30	-0.30	78.52	0.0150	T	Goldstone: 34mBWG, DSS25	
9	Ant Pointing Loss	dB	-0.10	0.00	0.00	-0.10	0.0000	U	n/a	LNA Selection
10	Polarization Loss	dB	-0.04	0.00	0.00	-0.04	0.0000	U	X/Ka, Diplex RCP	DSS Config
	TOTAL POWER SUMMARY									
11	Total Rcvd Pwr (Pt) (5+6+7+8+9+10)	dBm				-124.12	0.2344	G		
12	Noise Spec Dens	dBm/Hz	-179.72	-0.06	0.11	-179.70	0.0007	G		
	System Noise Temp	K	77.18	-1.00	2.00			G		
	Vacuum, zenith	K	32.91	-1.00	2.00			T	2	WAY
	Elevation	K	2.24	0.00	0.00			G		
	Sky	K	42.04	0.00	0.00			G		
	Hot Body Noise	K	0.00	0.00	0.00			G		
13	**Received Pt/No**	**dB-Hz**				**55.57**	**0.2352**	**G**		
13a	**Received Pt/No - 2sigma**	**dB-Hz**				**54.60**				
	CARRIER PERFORMANCE (actual)									
14	Tlm Carrier Supp	dB	-12.33	2.03	-2.71	-12.55	0.9446	T	TRUE	TLM ON?
15	Rng Carrier Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	0 deg	RNG MI?
16	DOR Carrier Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	FALSE	DOR ON?
17	Received Pc/No (13+14+15+16)	dB-Hz				43.02	1.1797	T		
18	Carrier Loop Bandwidth, Bl	dB-Hz	10.00	0.00	0.00	10.00	0.0000	T	10.0	Carrier Bl, Hz
18a	Phase Noise Variance	rad^2				0.00			-20.0	Carrier Phase Noise
	Thermal Noise Contribution	rad^2				0.0009			Type 2. SuperCritically Damped	ed
	Transmitter Noise Contribution	rad^2				0.0008				
	Solar Noise Contribution	rad^2				0.0000			Residual Carrier, Direct Carrier	
19	Loop SNR	dB				27.89	1.1797	U	Residual Carrier, Direct Carrier	
20	Required Carrier Loop SNR	dB				10.00	0.0000	D		
21	Carrier Loop SNR Margin	dB				17.89	1.1797	U		
	SUBCARRIER PERFORMANCE (actual)									
22	SubCar. L. SNR	dB				N/A				
23	Required Loop SNR	dB				N/A			N/A	SubCarr Bl, mHz
24	SubCarrier Loop SNR Margin	dB				N/A			N/A	SubCarr window f.
	SYMBOL LOOP PERFORMANCE (actual)									
25	Sym. Loop SNR	dB				49.99			50	Sym Bl, mHz
26	Required Loop SNR	dB				15.00			1	Sym window f.
27	SubCarrier Loop SNR Margin	dB				34.99				
	TELEMETRY PERFORMANCE (actual)									
28	Tlm Data Supp	dB	-0.26	0.12	-0.16	-0.28	0.0035	T	76.0	tlm MI, deg
29	Rng Data Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	0.00	peak rng MI, deg
30	DOR Data Supp	dB	0.00	0.00	0.00	0.00	0.0000	T		
30a	Pd/No (39 +28 +29 +30)	dB-Hz				55.30				
31	Data Rate	dB	51.46	0.00	0.00	51.46	0.0000	D	140000	data bit rate, bps
31a	Es/No	dB				-3.94			840000.00	ch symbol rate, bps
32	Radio Loss	dB	-0.07			-0.07		T		
33	SubCarrier Demod. Loss	dB	0.00			0.00		T		
34	Symbol Sync. Loss	dB	0.00			0.00		T		
35	Waveform Distortion Loss	dB	-0.15			-0.15		T		
36	Decoder loss	dB		placeholder		-0.30			Turbo 1/6, 8920 bit frar	
37	Output Eb/No	dB				3.32				
38a	Baseline Eb/No	dB				-0.10		D		Coding
38b	Eb/No margin	dB				3.42			FER=10^-4	BER at BVR output
39	Pt/No margin (for reference only)	dB				3.64	0.3060	**U**		
41	Sigma	dB				0.74				
42	Margin - 2 sigma (on telemetry)	dB				2.17				

Table C.5-2. *25 W X-band TWTA, MGA, 34 m array DSN, sun safing orientation.*

endoza

TITAN ORB Downlink Design Control Table

run date: 28-Aug-2008
dct version v5.2a

25.0 W TWTA

X-Band TITAN_MGA, 7.0° off-point
DSN 34 m station / MASER /Configuration: X/Ka non-diplexed
Goldstone/20 deg. elevation/90% CD Weather (Year Average)
Hot body noise = 5 K
1 way
Block V receiver/residual carrier mode/TLM-21 Models
Tlm channel/ (Turbo 1/2, 1784 bit frame)/ FER=10^-4

Carrier Loop Bandwidth = 0.5 Hz
Symbol Rate to the SDST= 40 sps
Data Bit Rate Before All Encoding= 20 bps

1.496E+09	Range, km
10.0000	Range, AU
1.39	OWLT, hrs
20.00	SEP, deg
20	Elev. Angle, deg

	Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var	S		
									X	RF band
									8400	Freq, MHz
	TRANSMITTER PARAMETERS									
1	S/C RF Power Output	dBm	43.98	0.28	-0.29	43.98	0.0136	T	25.0	Xmtr Pwr, W (BOL)
2	Total Circuit Loss	dB	-2.00	0.00	0.00	-2.00	0.0000	U		
3	Antenna Gain (on boresight)	dBi	22.00	0.00	0.00	22.00	0.0000	T	7.00	Boresight Angle, deg
4	Ant Pointing Loss	dB	-1.73	0.00	0.00	-1.73	0.0000	U	TITAN_MGA	S/C Antenna
5	EIRP (1+2+3+4)	dBm				62.24	0.0136			
	PATH PARAMETERS									
6	Space Loss	dB	-294.43	0.00	0.00	-294.43	0.0000	D		
7	Atmospheric Attn	dB	-0.13	0.00	0.00	-0.13	0.0000	D	90	Weather %
									Year Average	Distribution Type
	RECEIVER PARAMETERS									
8	DSN Antenna Gain	dBi	68.33	0.10	-0.20	68.29	0.0039	T	Goldstone: 34mBWG, DSS25	
9	Ant Pointing Loss	dB	-0.10	0.00	0.00	-0.10	0.0000	U	MASER	LNA Selection
10	Polarization Loss	dB	-0.03	0.00	0.00	-0.03	0.0000	U	X/Ka non-diplexed	DSS Config
8b	Array Gain	dB	2.80			2.80				
	TOTAL POWER SUMMARY									
11	Total Rcvd Pwr (Pt)	dBm				-161.36	0.0175	G		
	(5+6+7+8+9+10)									
12	Noise Spec Dens	dBm/Hz	-183.00	-0.12	0.23	-182.95	0.0033	G		
	System Noise Temp	K	36.29	-1.00	2.00			G		
	Vacuum, zenith	K	22.13	-1.00	2.00			T	1	WAY
	Elevation	K	0.70	0.00	0.00			G		
	Sky	K	8.46	0.00	0.00			G		
	Hot Body Noise	K	5.00	0.00	0.00			G		
13	**Received Pt/No**	**dB-Hz**				**21.59**	**0.0207**	**G**		
13a	**Received Pt/No - 2sigma**	**dB-Hz**				**21.30**				
	CARRIER PERFORMANCE (actual)									
14	Tlm Carrier Supp	dB	-9.22	2.42	-3.56	-9.60	1.5136	T	TRUE	TLM ON?
15	Rng Carrier Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	0 deg	RNG MI?
16	DOR Carrier Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	FALSE	DOR ON?
17	Received Pc/No (13+14+15+16)	dB-Hz				11.99	1.5343	T		
18	Carrier Loop Bandwidth, Bl	dB-Hz	-3.01	0.00	0.00	-3.01	0.0000	T	0.5	Carrier Bl, Hz
18a	Phase Noise Variance	rad^2				0.03			-60.0	Carrier Phase Noise
	Thermal Noise Contribution	rad^2				0.0289			Type 2. SuperCritically Damped	
	Transmitter Noise Contribution	rad^2				0.0001			Type 2. SuperCritically Damped	
	Solar Noise Contribution	rad^2				0.0000			Residual Carrier, with Subcarrier	
19	Loop SNR	dB				15.38	1.5343	U	Residual Carrier, with Subcarrie	
20	Required Carrier Loop SNR	dB				10.00	0.0000	D		
21	Carrier Loop SNR Margin	dB				5.38	1.5343	U		
	SUBCARRIER PERFORMANCE (actual)									
22	SubCar. L. SNR	dB				28.46				
23	Required Loop SNR	dB				20.00			250	SubCarr Bl, mHz
24	SubCarrier Loop SNR Margin	dB				8.46			0.25	SubCarr window f.
	SYMBOL LOOP PERFORMANCE (actual)									
25	Sym. Loop SNR	dB				26.92			50	Sym Bl, mHz
26	Required Loop SNR	dB				15.00			0.25	Sym window f.
27	SubCarrier Loop SNR Margin	dB				11.92				
	TELEMETRY PERFORMANCE (actual)									
28	Tlm Data Supp	dB	-0.55	0.32	-0.47	-0.60	0.0260	T	35.0	tlm MI, deg
29	Rng Data Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	0.00	peak rng MI, deg
30	DOR Data Supp	dB	0.00	0.00	0.00	0.00	0.0000	T		
30a	Pd/No (39 +28 +29 +30)	dB-Hz				20.99				
31	Data Rate	dB	13.01	0.00	0.00	13.01	0.0000	D	**20**	data bit rate, bps
31a	Es/No	dB				4.97			40.00	ch symbol rate, bps
32	Radio Loss	dB	-0.14			-0.14		T		
33	SubCarrier Demod. Loss	dB	-0.18			-0.18		T		
34	Symbol Sync. Loss	dB	-0.10			-0.10		T		
35	Waveform Distortion Loss	dB	-0.15			-0.15		T	Turbo 1/2, 1784 bit frar	
36	Decoder loss	dB		placeholder		0.00				
37	Output Eb/No	dB				7.41				
38a	Baseline Eb/No	dB				1.50		D		Coding
38b	Eb/No margin	dB				5.91			FER=10^-4	BER at BVR output
39	Pt/No margin (for reference only)	dB				4.45	0.3285	**U**		
41	Sigma	dB				0.59				
42	Margin - 2 sigma (on telemetry)	dB				3.26				

Table C.5-3. X-band uplink, HGA, 34 m DSN.

HGA Uplink
DSN 20 kW/34 m station /Configuration: X/Ka diplexed
Goldstone/20 deg. Elevation/95% CD Weather (Year Average)
X-Band HGA, 4 m antenna diameter, 0.00° off-point
Hot Body Noise: None

Command channel/uncoded, PB=1.E-5 2000.0000 bps
Sine wave subcarrier/new model

1.496E+09	Range, km
10.0000	Range, AU
1.39	OWLT, hrs
20.00	SEP, deg
20	Elev. Angle

	Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var	Shape	X 7150.753857	RF band Freq, MHz
	TRANSMITTER PARAMETERS									
1	Total Xmitter Pwr	dBm	73.01	0.50	-0.50	73.01	0.0417	T	20	Xmtr Pwr, kW
2	Xmitter Waveguide Loss	dB	-0.40	0.10	-0.10	-0.40	0.0017	T		
3	DSN Antenna Gain	dBi	67.00	0.20	-0.30	66.96	0.0106	T	Goldstone: 34mBWG, DSS25	
4	Ant Pointing Loss	dB	-0.10	0.00	0.00	-0.10	0.0000	U	X/Ka diplexed	DSS Config
5	EIRP (1+2+3+4)	dBm				139.47	0.0540			
	PATH PARAMETERS									
6	Space Loss	dB	-293.03	0.00	0.00	-293.03		D		
7	Atmospheric Attn	dB	-0.14	0.00	0.00	-0.14		D	95	Weather %
	RECEIVER PARAMETERS								Year Average	Distribution Type
8	Polarization Loss	dB	-0.03	0.00	0.00	-0.03	0.0000	U		
9	Ant Pointing Loss	dB	0.00	2.30	-2.30	0.00	1.7726	U		
10	S/C Antenna Gain	dBi	46.07	0.00	0.00	46.07	0.0000	T	0.73	3 dB Beamwidth
11	Lumped Ckt/Ant Loss	dB	-4.90	0.00	0.00	-4.90	0.0000	U	HGA	S/C Antenna
	TOTAL POWER SUMMARY									
12	Total Rcvd Pwr (Pt) (5+6+7+8+9+10+11)	dBm				-112.57	1.8266	G		
13	Noise Spec Dens	dBm/Hz	-171.98	-1.11	0.59	-172.23	0.0758	G		
	System Noise Temp	K	459.55	-103.43	67.43					
	Rcvr Noise Temp	K	262.58	-103.43	67.43					
	Rcvr Noise Figure	dB	2.80	-0.90	0.50				EOL Value	
	Loss Noise Contr.	K	196.16	0.00	0.00					
	Ant Noise Contr.	K	0.81	0.00	0.00					
14	**Rcvd Pt/No**	**dB-Hz**				**59.66**	**1.9024**	**G**	(12-13)	
14a	**Pt/No-3 sigma**					**55.52**				
	CARRIER PERFORMANCE									
15	Cmd Carrier Supp	dB	-5.82	0.58	-0.58	-5.82	0.0565	T	TRUE	CMD ON?
16	Rng Carrier Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	0 deg (0 dB)	RNG MI?
17	Rcvd Carr Power (Pc)	dBm				-118.39	1.8831	T	(12+15+16)	
17a	Pc/No	dB-Hz				53.84	1.9589			
18	Carr Noise BW, BL	dB-Hz	20.38	0.08	-0.08	20.37	0.0021	U	109.0	Bl, Hz
19	Required Carrier Loop SNR	dB	12.00			12.00		D		
20	Excess Carrier Loop SNR	dB				21.47	1.9610	U	(17-13-18-19)	
	CHANNEL PERFORMANCE									
21	Cmd Modulation Loss	dB	-2.06	0.12	-0.15	-2.07	0.0031	T	1.5	cmd MI, rad
22	Rng Data Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	0.00	rng MI, deg
23	Data Pwr to Rcvr (Pd)	dBm				-114.64	1.8296	T	(12+21+22)	
24	Data Rate	dB	33.01	0.00	0.00	33.01	0.0000	D	2000	data rate
25	System Loss	dB	-1.48	0.84	-0.75	-1.45	0.1056	T	(includes radio loss)	
26	Threshold Eb/No	dB	9.60			9.60		D	BER = 1e-5, uncoded	
27	Required Eb/No	dB				11.05				
28	**Required Pt/No**	**dB**				**46.13**	**0.4111**			
29	**Performance Margin**	**dB**				**13.53**			(14 - 28)	
30	Sigma					1.52				
31	Margin - 3 sigma	dB				8.97				

Table C.5-4. X-band downlink LGA, 70 m equivalent DSN, SOI carrier only.

endoza

TITAN ORB Downlink Design Control Table

run date: 28-Aug-2008
dct version v5.2a

25.0 W TWTA

X-Band CASLGA, 30.0° off-point
DSN 70 m station /Configuration: X/X
Goldstone/20 deg. elevation/90% CD Weather (Year Average)
Hot body noise = 5 K
1 way
Block V receiver/residual carrier mode/TLM-21 Models
Tlm channel/ (Uncoded)/ BER=1x10^-5

Carrier Loop Bandwidth = 0.5 Hz
Symbol Rate to the SDST= 5 sps
Data Bit Rate Before All Encoding= 5 bps

1.496E+09	Range, km
10.0000	Range, AU
1.39	OWLT, hrs
20.00	SEP, deg
20	Elev. Angle, deg

No.	Link Parameter	Unit	Design Value	Fav Tol	Adv Tol	Mean Value	Var	S		
									X	RF band
									8400	Freq, MHz
	TRANSMITTER PARAMETERS									
1	S/C RF Power Output	dBm	43.98	0.28	-0.29	43.98	0.0136	T	25.0	Xmtr Pwr, W (BOL)
2	Total Circuit Loss	dB	-2.00	0.00	0.00	-2.00	0.0000	U		
3	Antenna Gain (on boresight)	dBi	8.94	0.00	0.00	8.94	0.0000	T	30.00	Boresight Angle, deg
4	Ant Pointing Loss	dB	-3.13	-0.50	0.50	-3.13	0.0835	U	CASLGA	S/C Antenna
5	EIRP (1+2+3+4)	dBm				47.79	0.0971			
	PATH PARAMETERS									
6	Space Loss	dB	-294.43	0.00	0.00	-294.43	0.0000	D		
7	Atmospheric Attn	dB	-0.13	0.00	0.00	-0.13	0.0000	D	90	Weather %
									Year Average	Distribution Type
	RECEIVER PARAMETERS									
8	DSN Antenna Gain	dBi	74.43	0.10	-0.10	74.43	0.0017	T	Goldstone: 70m, DSS14	
9	Ant Pointing Loss	dB	-0.10	0.00	0.00	-0.10	0.0000	U	n/a	LNA Selection
10	Polarization Loss	dB	-0.01	0.00	0.00	-0.01	0.0000	U	X/X	DSS Config
	TOTAL POWER SUMMARY									
11	Total Rcvd Pwr (Pt)	dBm				-172.46	0.0988	G		
	(5+6+7+8+9+10)									
12	Noise Spec Dens	dBm/Hz	-183.88	0.14	-0.15	-183.88	0.0022	G		
	System Noise Temp	K	29.67	1.00	-1.00			G		
	Vacuum, zenith	K	11.63	1.00	-1.00			T	1	WAY
	Elevation	K	1.94	0.00	0.00			G		
	Sky	K	11.10	0.00	0.00			G		
	Hot Body Noise	K	5.00	0.00	0.00			G		
13	**Received Pt/No**	**dB-Hz**				**11.42**	**0.1010**	**G**		
13a	**Received Pt/No - 2sigma**	**dB-Hz**				**10.79**				
	CARRIER PERFORMANCE (actual)									
14	Tlm Carrier Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	FALSE	TLM ON?
15	Rng Carrier Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	0 deg	RNG MI?
16	DOR Carrier Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	FALSE	DOR ON?
17	Received Pc/No (13+14+15+16)	dB-Hz				11.42	0.1010	T		
18	Carrier Loop Bandwidth, Bl	dB-Hz	-3.01	0.00	0.00	-3.01	0.0000	T	0.5	Carrier Bl, Hz
18a	Phase Noise Variance	rad^2				0.15			-60.0	Carrier Phase Noise
	Thermal Noise Contribution	rad^2				0.1464			Type 2. SuperCritically Damped	
	Transmitter Noise Contribution	rad^2				0.0001			Type 2. SuperCritically Damped	
	Solar Noise Contribution	rad^2				0.0000			Residual Carrier, with Subcarrier	
19	Loop SNR	dB				8.34	0.1010	U	Residual Carrier, with Subcarrie	
20	Required Carrier Loop SNR	dB				10.00	0.0000	D		
21	Carrier Loop SNR Margin	dB				-1.66	0.1010	U		
	SUBCARRIER PERFORMANCE (actual)									
22	SubCar. L. SNR	dB				18.82				
23	Required Loop SNR	dB				20.00			250	SubCarr Bl, mHz
24	SubCarrier Loop SNR Margin	dB				-1.18			0.25	SubCarr window f.
	SYMBOL LOOP PERFORMANCE (actual)									
25	Sym. Loop SNR	dB				17.29			50	Sym Bl, mHz
26	Required Loop SNR	dB				15.00			0.25	Sym window f.
27	SubCarrier Loop SNR Margin	dB				2.29				
	TELEMETRY PERFORMANCE (actual)									
28	Tlm Data Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	0.0	tlm MI, deg
29	Rng Data Supp	dB	0.00	0.00	0.00	0.00	0.0000	T	0.00	peak rng MI, deg
30	DOR Data Supp	dB	0.00	0.00	0.00	0.00	0.0000	T		
30a	Pd/No (39 +28 +29 +30)	dB-Hz				11.42				
31	Data Rate	dB	0.00	0.00	0.00	0.00	0.0000	D	**5**	data bit rate, bps
31a	Es/No	dB				4.43			5.00	ch symbol rate, bps
32	Radio Loss	dB	0.00			0.00		T		
33	SubCarrier Demod. Loss	dB	-0.72			-0.72		T		
34	Symbol Sync. Loss	dB	-0.19			-0.19		T		
35	Waveform Distortion Loss	dB	-0.09			-0.09		T	Uncoded	
36	Decoder loss	dB		placeholder		0.00				
37	Output Eb/No	dB				10.42				
38a	Baseline Eb/No	dB				9.60		D		Coding
38b	Eb/No margin	dB				0.82			BER=1x10^-!	BER at BVR output
39	Pt/No margin (for reference only)	dB				0.49	0.3025	**U**		
41	Sigma	dB				0.64				
42	Margin - 2 sigma (on telemetry)	dB				-0.78				

Table C.5-5. *TSSM montgolfière relay link at 6.2e6 km.*

TSSM/Titan Balloon Relay Link DCT

Run Date: September 11, 2008

		Variables	Nominal	Fav Tol	Adv Tol	Mean	Variance
Transmitter Parameters							
1) TX Power: Fixed Xmit Pwr	Watts		25.00				
	dBm		44.0	0.8	-0.8	43.98	0.213
1a) Fixed Transmit Power	Watts	25.0					
2) TX Line and Antenna Ohmic Losses	dB	-1.7	-1.7	0.2	-0.2	-1.70	0.013
3) Transmit Antenna Gain / Directivity	dBi		31.0	1.0	-1.0	31.00	0.333
3a) Specified Fixed Antenna Gain	dBi	31					
4) EIRP	dBm		73.3			73.3	0.560
5) Modulation Index	deg	60.0				60.0	
5a) Scrambler => check box		☐					
Space Link Parameters							
6c) Satellite Cone Angle to Balloon	deg	58.2	58.2				
7) Slant Range	km	6200000.0	6200000.0				
8) 1-Way Light Time	msec		20681.0				
9) Link Frequency	MHz	7940.000					
10) Atmospheric Attenuation	dB	0.5	0.5	0	0	0.50	0.000
11) Space Losses	dB		-246.3			-246.29	
Receiver Parameters							
12) Polarization Loss	dB			1.00	-1.00	-1.00	0.333
13) Receiver Antenna Gain Toward User	dBi		47.00	1.50	-1.50	47.00	0.250
13a) Specified Fixed Antenna Gain / Directivity	dBi	47.0					
14) Antenna Ohmic Loss	dB	-2.0	-2.00	0.10	-0.10	-2.00	0.003
15) Cable Losses (Antenna to Receiver)	dB	-0.42	-0.42	0.10	-0.10	-0.42	0.003
16) Received Power, Xcvr Input	dBm		-128.93			-128.93	
17) Receiver Input to LNA Losses	dB		-2.02	0.38	-0.38	-2.02	0.047
18) Received Power, LNA Input	dBm		-130.95			-130.95	
19) Receiver Noise Figure at LNA Input	dB		1.87	-0.08	0.08	1.87	
20a) Titan Sky Temp	K	50.0		-40.00	40.00	18.01	
20b) Antenna Physical Temp.	K	290.0		-6.75	6.60	61.09	
20c) Cable Physical Temp.	K	290.0		-6.75	6.60	16.81	
20d) Electra Chassis Temp.	K	293.2		-26.44	24.25	108.82	
20e) LNA Temperature	K			-5.00	5.08	155.81	
20f) Total Noise Temperature at LNA Input	K		360.54	-84.94	82.54	359.34	
21) G/T @ LNA	dB-K					19.02	
22) Noise Spectral Density	dBm/Hz		-173.03	-1.17	0.90	-173.12	0.178
23) User Setting Loop Bandwidth	Hz	10.0				28	
Receiver Power							
24) AGC Loss	dB		0.00	0.20	-0.20	0.00	0.013
25) Net Received Pt/No	dB Hz		42.17			42.17	
26) Carrier Power/Total Power	dB		-6.02			-6.02	
27) Received Carrier Power	dBm		-136.97			-136.97	
28) Carrier SNR in 2Blo	dB		21.68			21.68	
Data Channel Performance							
29) Channel Symbol Rate	sps		2,000			2,000	
30) Channel Bit Rate	bps		1,000			1,000	
31) R-S Code Rate			0.92			0.92	
32) Data Bit Rate	bps		917			917	
33) Data Power/Total Power	dB		-1.25			-1.25	
34) Data Power to Receiver	dBm		-132.20			-132.20	
35) Eb/No to Receiver	dB		11.30			11.30	
36) Demod Loss	dB		-0.70	0.10	-0.10	-0.70	0.003
38) Eb/No Output	dB					10.60	
39) Es/No Output						7.21	
40) BER			1.86E-58				
41) BER out of Viterbi Decoder			1.95E-11				
41a) Prox-1 FER (16,384 bit frame)			N/A				
42a) Goal Eb/No if Used	NO	3.44					
42) Threshold Eb/No @ Decoder	dB		3.44			3.44	
43) Desired Margin	dB	6.00	6.00			6.00	
44) Performance Margin	dB		7.16			7.16	1.388
44a) 2-Sigma Perfomance Variation	dB					2.36	

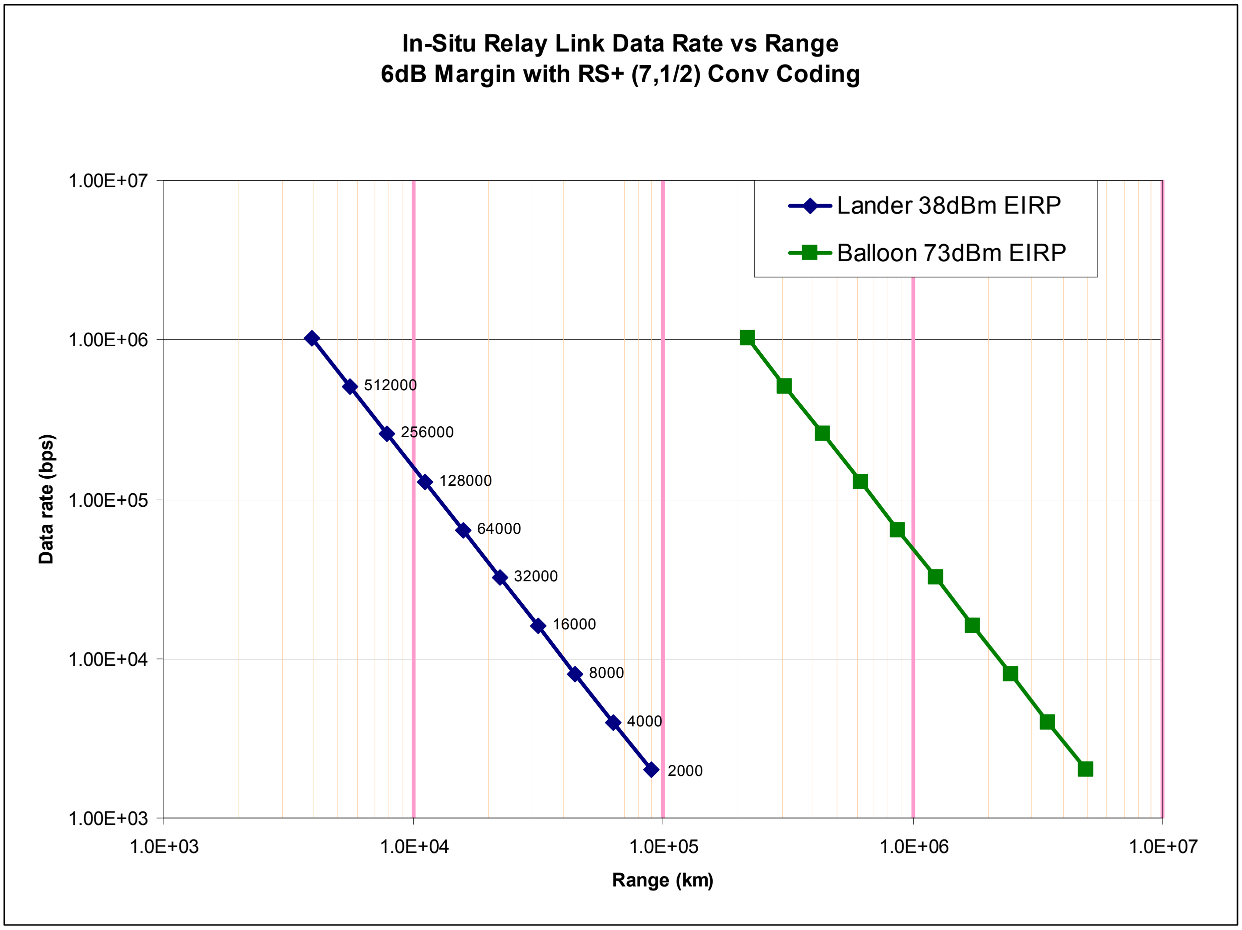
Table C.5-6. TSSM lander relay link at 89500 km.

TSSM/Titan Lander Link Budget

Run Date: September 11, 2008

		Variables	Nominal	Fav Tol	Adv Tol	Mean	Variance
Transmitter Parameters							
1) TX Power: Fixed Xmit Pwr	Watts		8.00				
	dBm		39.0	0.8	-0.8	39.03	0.213
1a) Fixed Transmit Power	Watts	8.0					
2) TX Line and Antenna Ohmic Losses	dB	-1.7	-1.7	0.2	-0.2	-1.70	0.013
3) Transmit Antenna Gain / Directivity	dBi		0.0	1.0	-1.0	0.00	0.333
3a) Specified Fixed Antenna Gain	dBi	0					
4) EIRP	dBm		37.3			37.3	0.560
5) Modulation Index	deg	60.0				60.0	
5a) Scrambler => check box		☐					
Space Link Parameters							
6c) Satellite Cone Angle to Lander	deg	58.2	58.2				
7) Slant Range	km	89500.0	89500.0				
8) 1-Way Light Time	msec		298.5				
9) Link Frequency	MHz	7940.000					
10) Atmospheric Attenuation	dB	0.5	0.5	0	0	0.50	0.000
11) Space Losses	dB		-209.5			-209.48	
Receiver Parameters							
12) Polarization Loss	dB			1.00	-1.00	-1.00	0.333
13) Receiver Antenna Gain Toward User	dBi		47.00	1.50	-1.50	47.00	0.250
13a) Specified Fixed Antenna Gain / Directivity	dBi	47.0					
14) Antenna Ohmic Loss	dB	-2.0	-2.00	0.10	-0.10	-2.00	0.003
15) Cable Losses (Antenna to Receiver)	dB	-0.42	-0.42	0.10	-0.10	-0.42	0.003
16) Received Power, Xcvr Input	dBm		-128.07			-128.07	
17) Receiver Input to LNA Losses	dB		-2.02	0.38	-0.38	-2.02	0.047
18) Received Power, LNA Input	dBm		-130.08			-130.08	
19) Receiver Noise Figure at LNA Input	dB		1.87	-0.08	0.08	1.87	
20a) Titan Sky Temp	K	50.0		-40.00	40.00	18.01	
20b) Antenna Physical Temp.	K	290.0		-6.75	6.60	61.09	
20c) Cable Physical Temp.	K	290.0		-6.75	6.60	16.81	
20d) Electra Chassis Temp.	K	293.2		-26.44	24.25	108.82	
20e) LNA Temperature	K			-5.00	5.08	155.81	
20f) Total Noise Temperature at LNA Input	K		360.54	-84.94	82.54	359.34	
21) G/T @ LNA	dB-K					19.02	
22) Noise Spectral Density	dBm/Hz		-173.03	-1.17	0.90	-173.12	0.178
23) User Setting Loop Bandwidth	Hz	10.0				57	
Receiver Power							
24) AGC Loss	dB		0.00	0.20	-0.20	0.00	0.013
25) Net Received Pt/No	dB Hz		43.04			43.04	
26) Carrier Power/Total Power	dB		-6.02			-6.02	
27) Received Carrier Power	dBm		-136.11			-136.11	
28) Carrier SNR in 2Blo	dB		19.46			19.46	
Data Channel Performance							
29) Channel Symbol Rate	sps		4,000			4,000	
30) Channel Bit Rate	bps		2,000			2,000	
31) R-S Code Rate			0.92			0.92	
32) Data Bit Rate	bps		1,834			1,834	
33) Data Power/Total Power	dB		-1.25			-1.25	
34) Data Power to Receiver	dBm		-131.33			-131.33	
35) Eb/No to Receiver	dB		9.15			9.15	
36) Demod Loss	dB		-0.70	0.10	-0.10	-0.70	0.003
38) Eb/No Output	dB					8.45	
39) Es/No Output						5.07	
40) BER			3.85E-44				
41) BER out of Viterbi Decoder			4.25E-09				
41a) Prox-1 FER (16,384 bit frame)			N/A				
42a) Goal Eb/No if Used	NO	3.44					
42) Threshold Eb/No @ Decoder	dB		3.44			3.44	
43) Desired Margin	dB	6.00	6.00			6.00	
44) Performance Margin	dB		5.01			5.01	1.388
44a) 2-Sigma Perfomance Variation	dB					2.36	

Figure C.5-1. *TSSM in situ element relay link data rates.*



D. COST DETAIL

Details not available for public release.

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E. FLIGHT SYSTEM DESIGN SUPPORTING DETAIL

E.1 Baseline TSSM Flight System

Figures E.1-1 through E.1-4 highlight several of the TSSM subsystem designs.

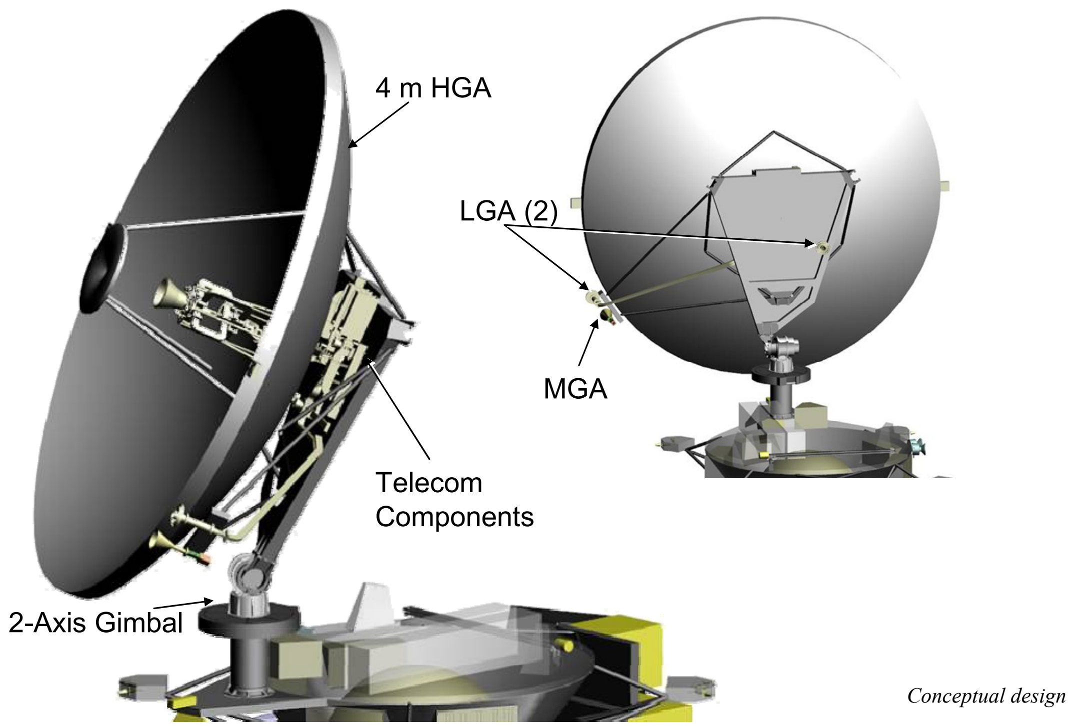


Figure E.1-1. Telecom configuration of the TSSM Flight System.

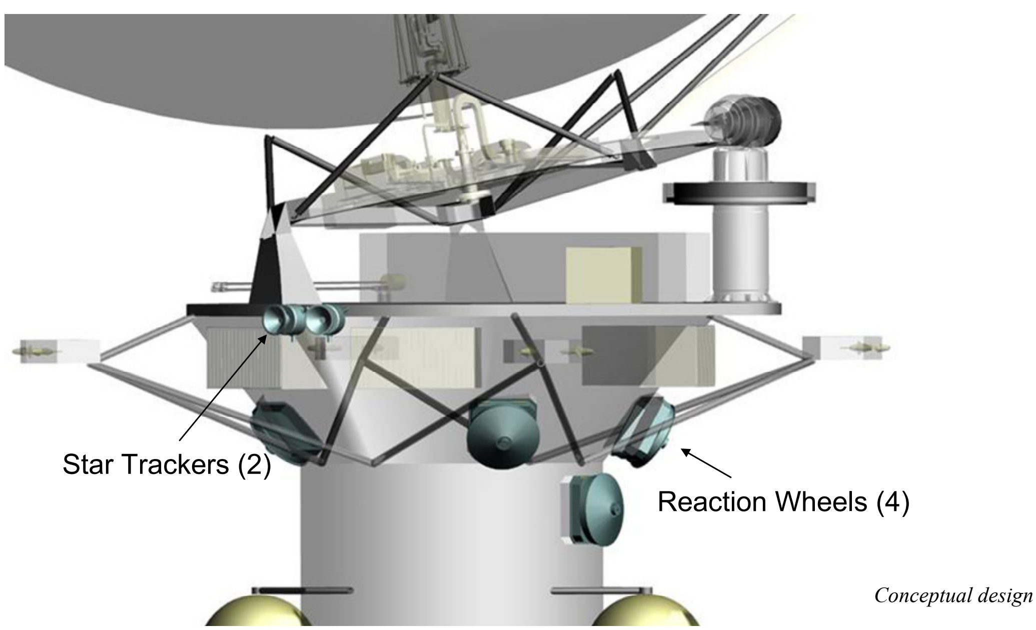


Figure E.1-2. ACS subsystem configuration of the TSSM Flight System.

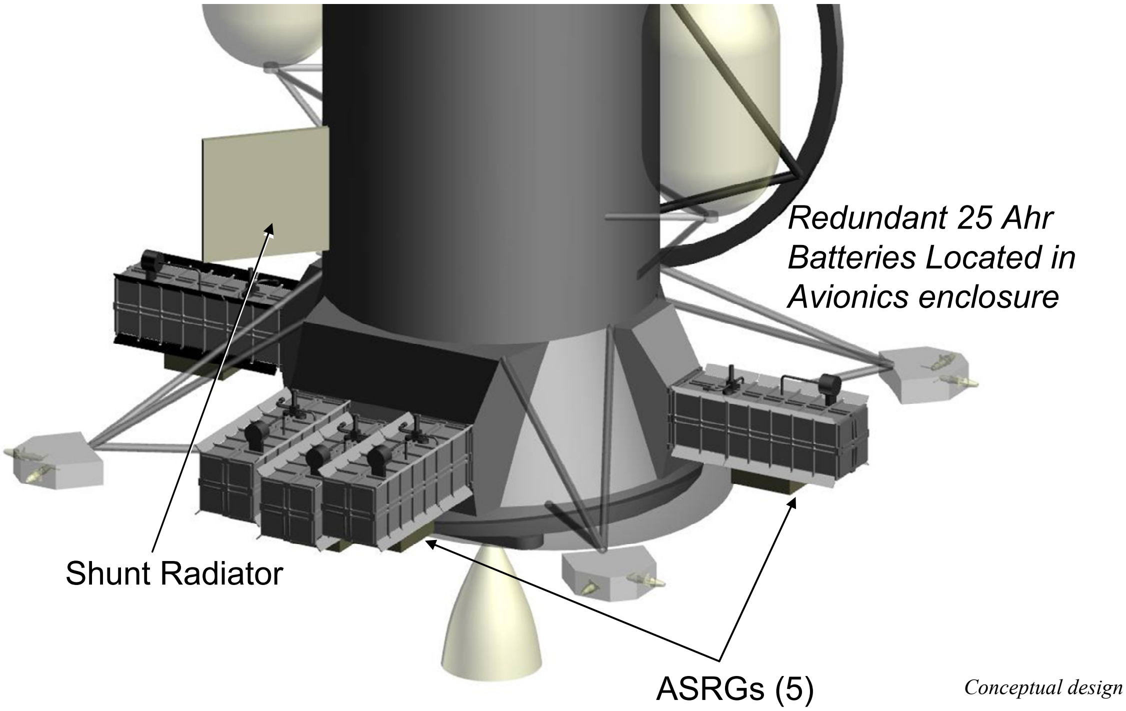


Figure E.1-3. *Power subsystem configuration of the TSSM Flight System.*

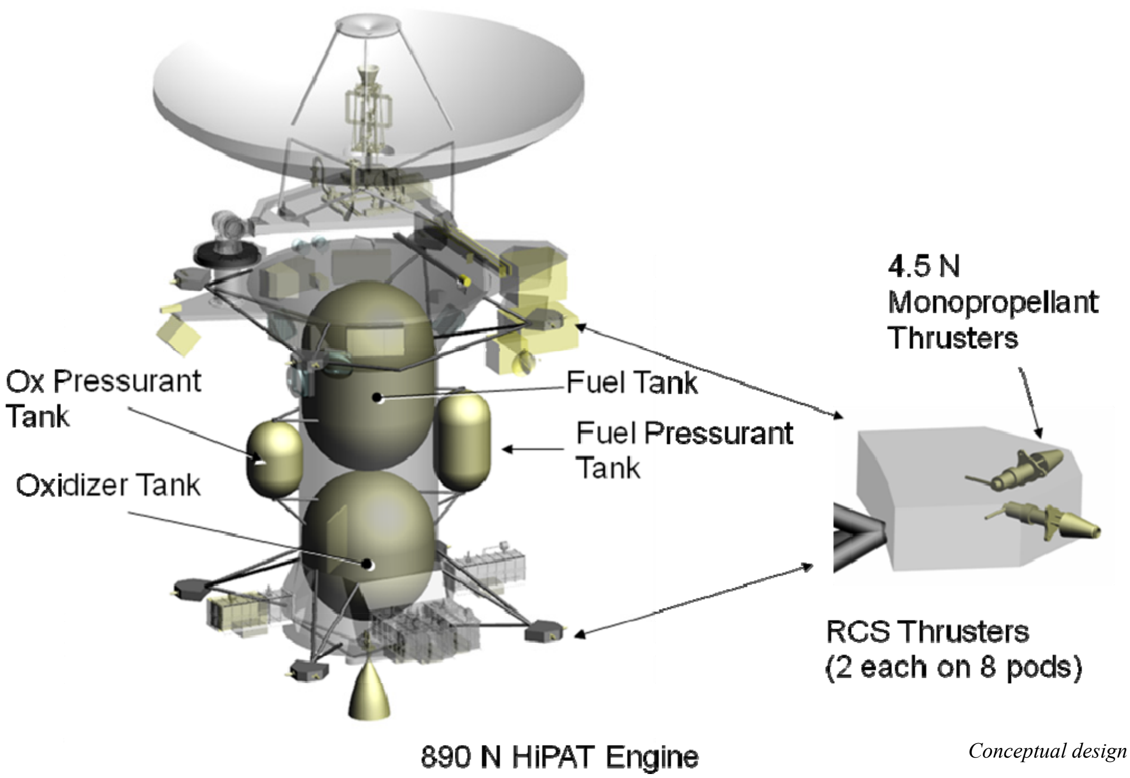


Figure E.1-4. *Propulsion subsystem configuration of the TSSM Flight System.*

E.2 Alternate Architecture Options

Several alternate architecture options are discussed as potential descopes for the TSSM mission. These options are discussed in detail in §3.3.1.2.

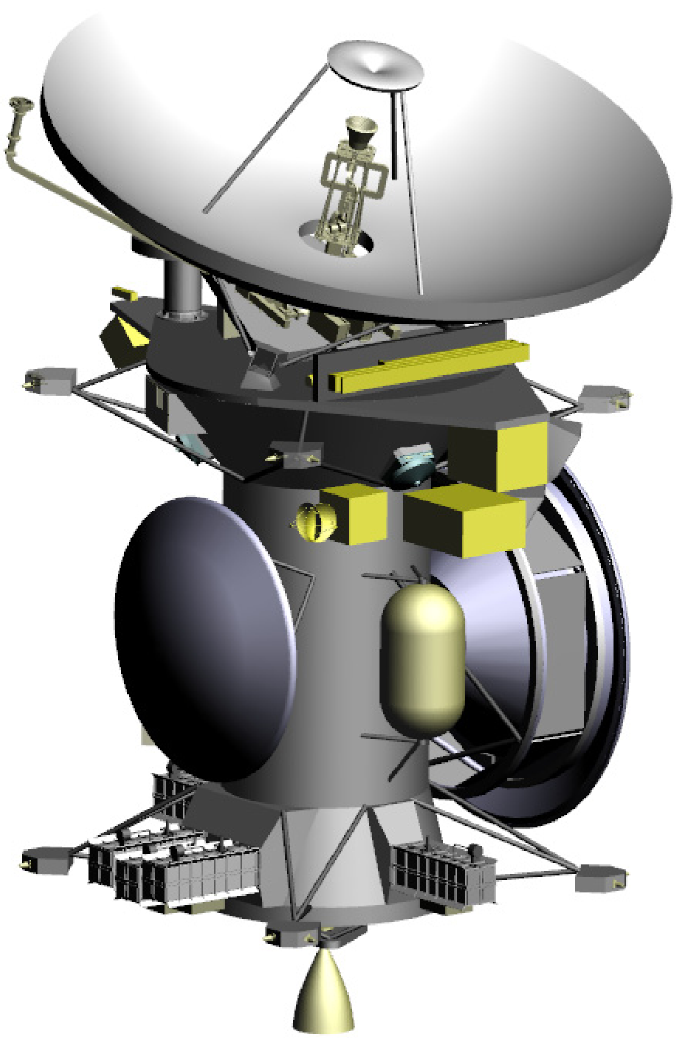
E.2.1 NASA/ESA Floor Mission

The NASA/ESA Floor mission is an all-chemical propulsion option (no SEP system), which includes both the montgolfière balloon and short-lived lander *in situ* elements provided by ESA. **Table E.2-1** shows a mass summary for the NASA/ESA Floor mission and **Figure E.2-1** shows the corresponding configuration.

The propellant load (2047 kg) and launch vehicle capability (4740 kg) shown in the example MEL (**Table E.2-1**), are from the November 2020 EVEE chemical trajectory option shown in **Table 5.2-2**.

Table E.2-1. *NASA/ESA Floor mission mass summary.*

TSSM NASA/ESA Floor Mission MEL	Flight System Mass, kg			Comments
	CBE	Cont.	CBE + Cont.	
Orbiter Payload	108	33%	143	
Instrument Planning Payload	108	33%	143	HiRIS, TIPRA, PMS, SMS, TIRS, MAPP, RSA
Orbiter Flight System	952	31%	1244	
Power (w/o RPS)	64	30%	83	Power distribution, converters, & switches, and 25 Ahr battery
C&DH	32	17%	37	Redundant Rad750 SFC and 32Gb SDRAM for science
Telecom	64	27%	82	X/Ka 4m HGA, X MGA & LGAs, 35W Ka and 25W X TWTAs
Structures & Mechanisms	349	30%	455	S/C structure, In-situ support, HGA gimbal, & mag boom
Thermal	82	30%	106	Capillary loop heat pipes, Venus shield, shunt radiator, and (V)RHUs
Propulsion	135	27%	171	890N main engine, RCS thrusters, and COPV tanks
ACS	53	21%	64	Reaction wheels, SIRU, star trackers, sun sensors, and OpNav
Cabling	67	30%	87	7% of CBE S/C bus dry mass
RPS System	107	49%	160	Five ASRGs
Orbiter Total Dry	1060	31%	1387	Includes P/L, bus, and subsystem contingency
Additional System Margin			194	Additional cont. on S/C bus and P/L to obtain 33% margin
Orbiter Total Dry with req'd margin			1581	Includes P/L, bus, and system contingency
Orbiter Propellant			2047	Fuel cooresponding to 11/2020 chemical-only trajectory
Orbiter Total Wet			3628	
ESA-Provided In-Situ Packages	833	0%	833	Includes ESA-provided spin ejection devices for each in-situ
Montgolfiere Balloon (plus spin eject device)	633	0%	633	Released at beginning of tour (post-SOI)
Lander (plus spin eject device)	200	0%	200	Released mid-tour (post SOI)
Orbiter + In-Situ Total (Wet)			4461	Orbiter & in-situ P/L, flight system, prop, and all contingency
SEP System			0	No SEP on NASA/ESA Floor Mission
LV Adapter with required margin			123	Separate LV Adapter required if no SEP system
Total Launch Mass			4584	Entire wet spacecraft including In-situ, SEP stage, adapters, and contingencies
Atlas V 551 Capability			4740	EVEE trajectory launched in November 2020 on Atlas V 551
Additional Mass Margin			156	Mass margin beyond the required 33% margin
System Margin (33% required per study guidelines)			39%	TSSM accomodates an ample orbiter P/L & In-Situ Elements with sufficient margin



Conceptual design

Figure E.2-1. *NASA/ESA Floor mission configuration.*

E.2.2 NASA-only Mission

The NASA-only mission consists of the orbiter flight system and SEP propulsive stage, but does not deliver any *in situ* elements to Titan. **Table E.2-2** shows a mass summary for the NASA-only mission and **Figure E.2-2** shows the corresponding configuration. This MEL assumes the same propellant and trajectory as in the baseline TSSM design.

Table E.2-2. *NASA-only mission mass summary.*

TSSM NASA-Only Mission MEL	Flight System Mass, kg			Comments
	CBE	Cont.	CBE + Cont.	
Orbiter Payload	108	33%	143	
Instrument Planning Payload	108	33%	143	HiRIS, TIPRA, PMS, SMS, TIRS, MAPP, RSA
Orbiter Flight System	949	31%	1241	
Power (w/o RPS)	64	30%	83	Power distribution, converters, & switches, and 25 Ahr battery
C&DH	32	17%	37	Redundant Rad750 SFC and 32Gb SDRAM for science
Telecom	64	27%	82	X/Ka 4m HGA, X MGA & LGAs, 35W Ka and 25W X TWTAs
Structures & Mechanisms	327	30%	427	S/C structure, In-situ support, HGA gimbal, & mag boom
Thermal	82	30%	106	Capillary loop heat pipes, Venus shield, shunt radiator, and (V)RHUs
Propulsion	154	27%	196	890N main engine, RCS thrusters, and COPV tanks
ACS	53	21%	64	Reaction wheels, SIRU, star trackers, sun sensors, and OpNav
Cabling	66	30%	86	7% of CBE S/C bus dry mass
RPS System	107	49%	160	Five ASRGs
Orbiter Total Dry	1057	31%	1383	Includes P/L, bus, and subsystem contingency
Additional System Margin			194	Additional cont. on S/C bus and P/L to obtain 33% margin
Orbiter Total Dry with req'd margin			1577	Includes P/L, bus, and system contingency
Orbiter Propellant			2528	Fuel, oxidizer, pressurant, residuals/holdup, and RCS prop
Orbiter Total Wet			4106	
ESA-Provided In-Situ Packages			0	No in-situ on NASA-Only Mission
Orbiter Total (Wet)			4106	Orbiter P/L, flight system, prop, and all contingency
SEP System	502	31%	655	
Power	96	30%	124	Two 7.5 kW solar array wings
C&DH	8	18%	10	REUs and PCUs
Structures & Mechanisms	154	29%	199	SEP structure doubles as LV adapter, Thruster & solar array gimbals
Thermal	38	47%	56	Tank and structure MLI, temp sensors, heaters, and PPU radiator
Propulsion	168	30%	218	Three NEXT-based ion thrusters with PPU and Xenon tankage
ACS	3	10%	3	Gimbal drive electronics
Cabling	34	30%	44	Includes SEP to orbiter cabling and harnesses to HVPA, PPU, etc.
LV Adapter (on SEP Stage)	20	30%	26	Non-structural elements of the LV adapter (fasteners, blankets, etc.)
SEP Stage Total Dry			681	Includes SEP system, LV adapter, and subsystem contingency
Additional System Margin			97	Additional cont. on SEP system & LV adapter to obtain 33% margin
SEP Stage Total Dry with req'd margin			778	Includes P/L, bus, and system contingency
SEP Propellant			451	Includes 10% additional propellant for margin
SEP Stage Total Wet			1229	Wet SEP stage with contingency to achieve 33% study margin
Total Launch Mass			5334	Entire wet spacecraft including SEP stage, adapters, and contingencies
Atlas V 551 Capability			6265	EVEES SEP trajectory launched in 2020 on Atlas V 551
Additional Mass Margin			931	Mass margin beyond the required 33% margin
System Margin (33% required per study guidelines)			52%	TSSM accomodates a SEP stage, an ample orbiter P/L & In-Situ Elements with sufficient margin

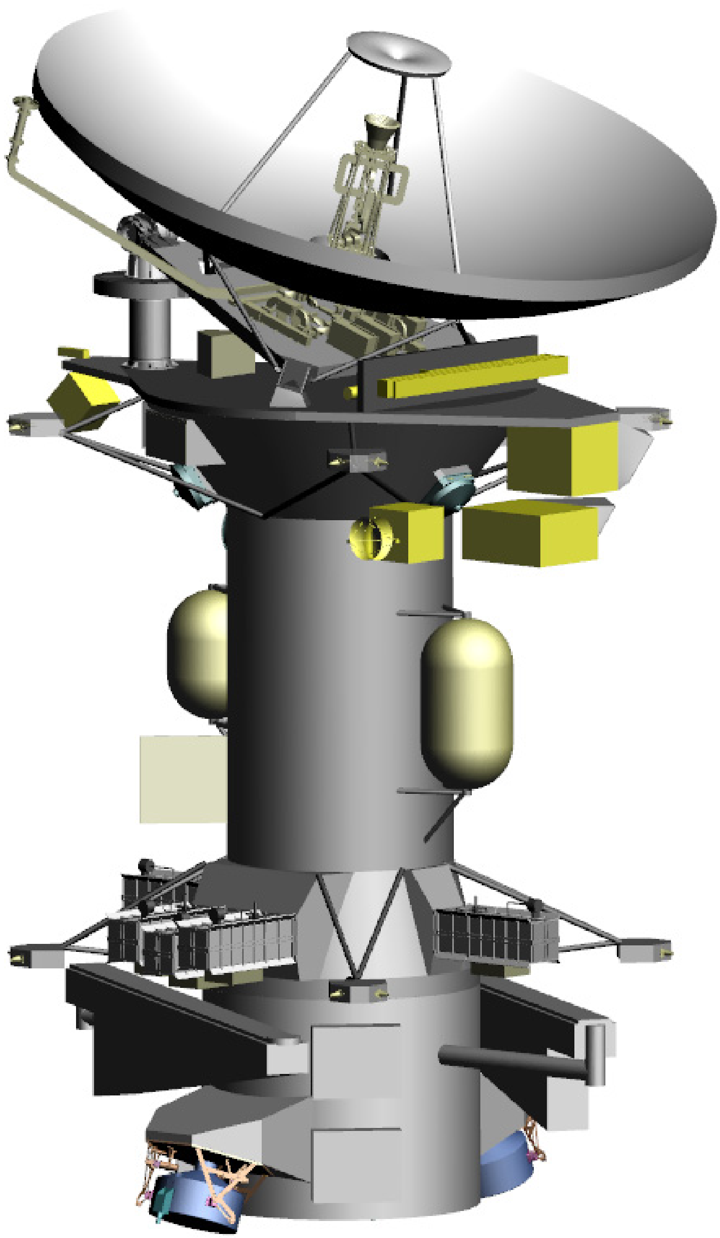


Figure E.2-2. *NASA-only mission configuration.*

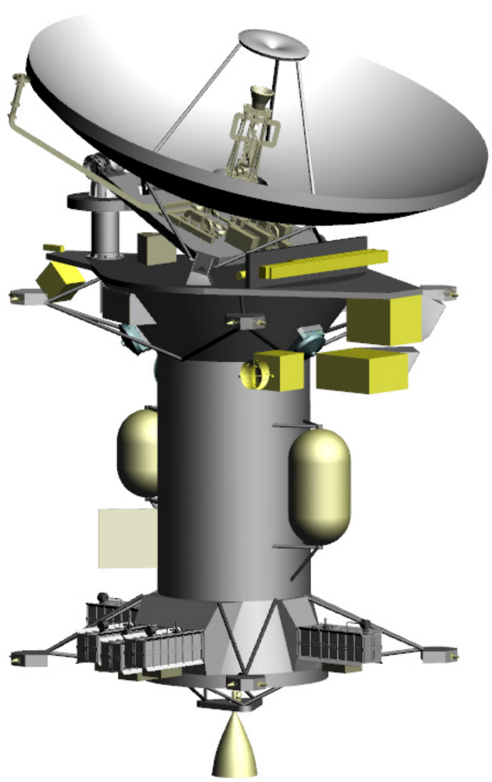
E.2.3 NASA-only Floor Mission

The NASA-only Floor mission does not have a SEP stage and does not carry any *in situ* elements to Titan. **Table E.2-3** shows a mass summary for the NASA-only Floor mission and **Figure E.2-3** shows the corresponding configuration.

This MEL assumes the worst-case propellant load (2450 kg plus pressurant) for any of the chemical trajectories studied between the 2018-2022 timeframe and the worst-case launch vehicle capability (4525 kg) of any of the alternate chemical trajectories discussed in **Table 5.2-2**.

Table E.2-3. *NASA-only Floor mission mass summary.*

TSSM NASA-Only Floor Mission MEL	Flight System Mass, kg			Comments
	CBE	Cont.	CBE + Cont.	
Orbiter Payload	108	33%	143	
Instrument Planning Payload	108	33%	143	HiRIS, TIPRA, PMS, SMS, TIRS, MAPP, RSA
Orbiter Flight System	946	31%	1236	
Power (w/o RPS)	64	30%	83	Power distribution, converters, & switches, and 25 Ahr battery
C&DH	32	17%	37	Redundant Rad750 SFC and 32Gb SDRAM for science
Telecom	64	27%	82	X/Ka 4m HGA, X MGA & LGAs, 35W Ka and 25W X TWTAs
Structures & Mechanisms	327	30%	427	S/C structure, In-situ support, HGA gimbal, & mag boom
Thermal	82	30%	106	Capillary loop heat pipes, Venus shield, shunt radiator, and (V)RHUs
Propulsion	151	27%	192	890N main engine, RCS thrusters, and COPV tanks
ACS	53	21%	64	Reaction wheels, SIRU, star trackers, sun sensors, and OpNav
Cabling	66	30%	86	7% of CBE S/C bus dry mass
RPS System	107	49%	160	Five ASRGs
Orbiter Total Dry	1053	31%	1379	Includes P/L, bus, and subsystem contingency
Additional System Margin			193	Additional cont. on S/C bus and P/L to obtain 33% margin
Orbiter Total Dry with req'd margin			1572	Includes P/L, bus, and system contingency
Orbiter Propellant			2461	Fuel to accommodate ANY chemical back-up trajectory in 2018-2022
ESA-Provided In-Situ Packages			0	No in-situ on the NASA-Only Floor Mission
SEP System			0	No SEP on the NASA-Only Floor Mission
Orbiter Total Wet			4034	
LV Adapter with required margin			123	Separate LV Adapter required if no SEP system
Total Launch Mass			4156	Entire wet spacecraft including In-situ, SEP stage, adapters, and contingencies
Atlas V 551 Capability			4525	Worst-case (lowest) LV capability from backup trajectory options
Additional Mass Margin			369	Mass margin beyond the required 33% margin
System Margin (33% required per study guidelines)			46%	TSSM accomodates an ample orbiter P/L with sufficient margin

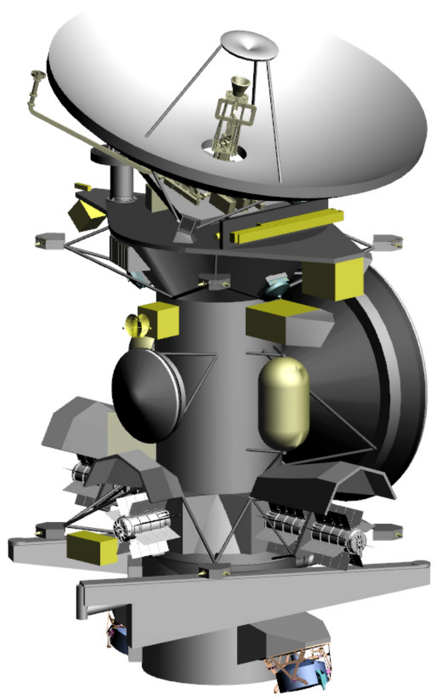


Conceptual design

Figure E.2-3. *NASA-only Floor mission configuration.*

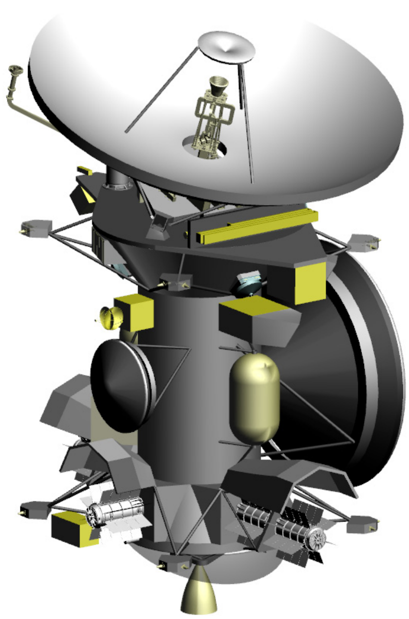
E.2.4 TSSM Baseline with MMRTGs

If TSSM was directed to use MMRTGs instead of ASRGs, the MMRTGs could be easily accommodated back into the TSSM design (this option was studied thoroughly at the beginning of this year's study). A discussion of the mass and power impacts of reverting to the MMRTG design is in §4.4.2.9. The configuration for this option is shown here in **Figure E.2-4** and **Figure E.2-5**



Conceptual design

Figure E.2-4. *MMRTG configuration on the NASA/ESA Baseline mission.*



Conceptual design

Figure E.2-5. *MMRTG configuration on the NASA/ESA Floor mission.*

F. PREVIOUS MISSION STUDIES

This study follows a series of Titan mission studies conducted since the mid-1990s. The reports from most are publicly available via the Internet, so they are summarized here only briefly. Six studies are cogent to the current study: the 2002 Aerocapture Systems Analysis Team's Titan Orbiter Study; the 2004 Titan Organic Exploration Study (TOES) under NASA's Vision Missions Program; TOES' follow-on study, the 2006 Titan Prebiotic Explorer (TiPEx) study; the 2007 "Billion Dollar Box" study; the 2007 Titan Explorer NASA Flagship Mission Study; and the 2007 Enceladus Explorer NASA Flagship Mission Study.

F.1 Aerocapture Systems Analysis Team Titan Orbiter

In fiscal year 2002, NASA's newly-formed Aerocapture System Analysis Team (ASAT) performed the first moderate-fidelity engineering design study of an aerocapture-based Titan Orbiter mission concept, with emphasis on the aerocapture flight systems and operations. At the time the "leveraged ΔV" pumpdown technique was not available so the ΔV for a propulsive orbit insertion at Titan appeared prohibitive. There was no Science Definition Team for the study, so notes from pre-draft meetings of SSE Decadal Survey Team were used to generate a notional list of science objectives.

F.2 Titan Organic Exploration Study (TOES) NASA Vision Missions

As a part of its 2003–2004 Vision Missions Program of studies, NASA awarded a task to study various techniques for atmospheric and surface access at Titan. This study assumed an orbiter and then focused on the *in situ* approaches, especially the hardware necessary for *in situ* observations and sampling. It led directly to the TiPEx study.

F.3 Titan Pre-biotic Explorer (TiPEx)

A follow-on study to the TOES study above, the 2006 TiPEx study examined every major aspect of an aerocaptured-orbiter-plus-balloon mission to Titan, including trajectories, flight system hardware, telecommunications and ground system requirements, operations concepts, and science. The science analyses included a thorough examination of science objectives, traced to the completed 2003 SSE Decadal Survey and also to high-level mission and system requirements.

F.4 "Billion Dollar Box"

In the light of spectacular Cassini/Huygens discoveries in the Saturn system, notably at Titan and Enceladus, NASA's Science Missions Directorate wanted to determine if any scientifically viable missions to either of these destinations might fit within the resource constraints of the New Frontiers Program. This groundbreaking study explored all viable architecture options and found, to the surprise of the planetary science community, that there are none *to these particular destinations*.

F.5 Titan Explorer

The immediate precursor to the TSSM Study, this NASA-commissioned, APL-led study examined in detail an aerocapture-based NASA Flagship mission concept that would deliver an orbiter, a lander, and a balloon to Titan, with a total mission cost significantly greater than that allowed for the current study. Science goals for the study were limited to Titan only; Saturn system and Enceladus science was not included.

F.6 Enceladus Explorer: NASA Flagship Mission Study

Conducted in parallel with the Titan Explorer study, this GSFC-led study examined mission concepts for detailed observation and study of Enceladus by a NASA Flagship mission. Like Europa, Enceladus lacks a usable atmosphere, so aerocapture into Enceladus orbit is not feasible, and this study pointed out the extreme difficulty in using straightforward propulsive capture. At this time, NASA is not pursuing further studies of a dedicated Enceladus Flagship mission, and the task of performing next-step Enceladus science has been subsumed into TSSM.

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G. INTERNATIONAL CONTEXT

NASA included as one of its guidelines for this study international collaboration with ESA for provision of *in situ* elements, as further described in the Ground Rules (NASA 2008). There are ample indications that the TSSM, like Cassini/Huygens, could have a broader international collaboration in flight hardware and engineering as well as scientific involvement. With its sizeable Solar System Exploration budget NASA is expected to be the primary source of funding for a Flagship outer planets mission. But despite their smaller overall budgets, space-faring organizations outside the US could make significant additional contributions to the flight systems, operations, and science of such a mission.

G.1 Space-Faring Organizations Outside the United States

There are multiple non-US space-faring organizations that could participate at various levels, ranging from large, well-financed efforts such as the European Space Agency (ESA) to fledgling programs that have not yet ventured on their own beyond Earth orbit. The following subsections describe first the agencies considered "prime candidates," and then other agencies that might make smaller contributions.

ESA

ESA is the primary agency for space flight and research of the European Union (EU), with financial support from the EU and its Member States. It has a significant yearly budget for exploration and scientific research. With its demonstrated capabilities for flight system development and fabrication, launch, and deep space operations, ESA is fully capable of conducting robotic interplanetary science missions on its own, as demonstrated by such missions as Rosetta, Mars Express, and Venus Express. With the success of the Huygens probe it has also demonstrated the capability to develop and fabricate vehicles that can survive entry into Titan's atmosphere, and survive and operate in Titan's atmospheric and surface environment. ESA's launch capability does not include launch vehicles as large as the largest in NASA's stable, but its largest, the Ariane 5, has sufficient launch capacity to deliver a scientifically viable spacecraft to the Saturn system via gravity assists in the inner solar system and possibly Jupiter. However, ESA currently cannot fabricate a radioisotope power source (RPS) sufficient to power a spacecraft for a long-lived mission beyond Jupiter, and French law currently prohibits launch of RPSs from ESA's primary launch facility in Kourou, French Guiana. If ESA contributes a long-lived flight element requiring an RPS of more than a few Watts electrical output, under current schedules the US would have to supply it, and under current laws and policies it would have to launch on a US launch vehicle. But the French laws that prohibit launches of nuclear materials from Kourou are being reviewed, and ESA is actively studying the resources needed to enable such launches.

ESA Member States

ESA is not the only space agency within the EU: multiple EU Member States also have their own national space agencies, such as France's CNES, Germany's DLR, and Italy's ASI. They have their own budgets and their own histories of flight experience. CNES has significant experience with successful scientific balloons, including balloons at Mars and Venus. Germany's DLR has developed space propulsion system components and scientific instruments designed to operate in the outer solar system, both certified for flight on Flagship US missions (Galileo and Cassini) with demonstrated success. ASI has significant experience with advanced spacecraft radio systems, providing major components of the Cassini telecommunications and radio science systems. They also built and flew, with Dutch collaboration and US launch, the successful BeppoSax X-ray observatory. Member states can also provide scientific expertise, as they have for Cassini/Huygens.

JAXA

The Japanese Aerospace Exploration Agency (JAXA), like ESA, has demonstrated flight system development and fabrication, launch, and deep space operations capabilities on their own (though with a lesser degree of success so far). JAXA has expressed a strong desire to collaborate with ESA in magnetospheric research, specifically proposing to provide a Jupiter-orbiting magnetospheric research flight element that might ride on an ESA (possibly with NASA involvement)

Jupiter mission, as mentioned in §G.2. JAXA cannot provide RPSs or the launch capacity to reach Saturn, so they would also be dependent on a US RPS and thus a US launch (under current law) for a long-lived mission element.

Other National Space Agencies

There are four other national space agencies with capability to provide contributions such as flight elements to an international outer planet mission, though others are rapidly developing their capabilities. The four are the Canadian Space Agency (CSA), the Russian Space Research Institute (IKI), the Indian Space Research Organization (ISRO) under India's Inter-Ministerial Space Commission, and the China National Space Administration (CNSA). Canada, though lacking its own launch capability, has a long history of building its own Earth-orbiting robotic spacecraft and other flight hardware such as the robotic arms on the US Space Shuttle and International Space Station. Its government agency CSA (ASC in French) was established in 1989. CSA has had the Microvariability and Oscillation of Stars (MOST) observatory satellite in operation since 2005, and plans to launch in 2009 the Near Earth Object Surveillance Satellite (NEOSSat), confirming CSA's ability to build scientific instruments and conduct scientific investigations in space. Canada also has a well-established program of space science research and could contribute scientists to a TSSM science team.

Born in the days of the Soviet Union, the Russian agency formerly had significant capabilities commensurate with a large budget: a well-established research program, demonstrated flight system development, fabrication, launch, and deep space operations capability, and fabrication and launch of RPSs. But there were severe budgetary cutbacks after the collapse of the USSR, reducing Russian scientific space activity to a small fraction of its former level. IKI personnel have suggested the intent to recapture some of the pre-USSR-collapse scope.

ISRO currently has limited launch and deep space operations capability limited to cislunar space, but has long-range plans that include the lead role in an orbiter mission to Mars. Their next planned planetary mission, Chandrayaan, is a lunar mission, their first foray beyond geostationary orbit.

CNSA has significant launch capability, but its deep space operations capabilities appear driven by a strong effort toward a manned exploration program in cislunar space. There is no apparent effort in science extending beyond cislunar space.

G.2 ESA's Cosmic Vision 2015–2025 Programme

ESA usually performs its long-term planning in approximately 10 year segments. They are nearly three years into the current planning activity, the *Cosmic Vision 2015–2025* (CV) Program, whose goal is to plan ESA's space science program for the 2015–2025 period. CV began with a call to the European space science community to propose high-priority science themes to be addressed in the CV time frame. ESA considered those proposed themes and produced a document, *Cosmic Vision: Space Science for Europe 2015–2025*, to list and describe the themes selected for subsequent steps of the process. For the science community the next step was to prepare proposals for studies of mission concepts to address the science themes. The proposals were for *studies* of mission concepts to provide ESA with sufficient information to make selections for implementation later in the process. Acceptance of the study proposal was by no means a confirmation that the proposed concept would actually fly. Note that this was not just for planetary science: all branches of space science, such as astronomy and astrophysics, and heliospheric studies, were included, so a wide range of mission types were involved.

ESA classifies its major science missions into Small-, Medium-, and Large-class missions, denoted S, M, and L respectively. The mission-related goal of CV is to plan ESA's M and L missions for the 2015–2025 time frame. Cost caps are associated with the classes, with M limited to 350M Euros and L to 650M Euros. These are costs to ESA, which in general are not total mission costs. For ESA missions, ESA usually provides (i.e., finances) the spacecraft, the launch vehicle, and other "standard" mission items and services, but not the science instruments and some other items that are contributed by European Union Member States at no cost to ESA. There are no well-

defined rules for which components, systems, or services the Member States contribute. Each mission is negotiated with a unique agreement.

Science community teams proposing science objectives and mission concepts in response to the call for proposals were required to declare the mission size class for their concept. Outer solar system (OSS) missions are difficult, so credible OSS mission concepts are all L-class missions. Even then, there are few scientifically viable missions to outer solar system destinations that can be flown within a cost of 650M Euros plus Member State contributions.

ESA received three such proposals and accepted two for studies: LaPlace, a mission to Europa and the Jupiter System, and TandEM, a Titan and Enceladus mission. The decision was not made without regard to NASA. ESA was aware of NASA's interest in an outer solar system Flagship mission, and the LaPlace/TandEM selections mirror NASA's stated interests at the time. With new Cassini/Huygens successes being announced on an almost daily basis, there is strong motivation among the planetary science community and many space agency administrators to make the next outer solar system Flagship mission another international collaboration, in the spirit of Cassini/Huygens.

Negotiations among the US, NASA, the EU, and ESA led to the structure of NASA's and ESA's current outer planet Flagship studies. For the Jupiter system, the LaPlace concept's Europa-orbiting element is replaced by a US Europa Orbiter currently under study, and the US Jupiter System Observer (JSO) concept is subsumed into LaPlace's ESA Jupiter orbiter (that might also orbit Ganymede), under study by ESA. JAXA might also provide a Jupiter-orbiting element for conducting Jovian magnetospheric investigations. For the Saturn system, a recasting of NASA's Titan Explorer and Enceladus Explorer concepts, along with ESA's TandEM concept, as a single mission, assigns a Titan orbiter to NASA and one or more *in situ* elements to ESA. To date JAXA has not approached NASA or ESA concerning a collaboration for a Saturn system mission. This establishes the foundation and structure for the TSSM study and associated studies by ESA.

Although at the initiation of this study there was a schedule misalignment between NASA's and ESA's development schedules, this has been resolved via the regular NASA/ESA bilateral discussions. New Ground Rules originating in those discussions target a 2020 launch date with options for 2018-2022 launches. The flexibility inherent in the TSSM architecture provides robustness against potential future schedule problems arising from programmatic, technical or cost issues. Examples of this flexibility include:

- SEP allows launch opportunities in every year
- Simple and clean interface allows separate parallel development of orbiter and *in* situ element, so changes in schedule do not significantly impact the flight elements
- Separate launch architectures, that would further decouple the development schedules, are possible but have not been examined in detail (see §3.3.2.4)

G.3 NASA/ESA Collaboration Potential

Both NASA and ESA have expressed interest in a collaborative Flagship/L-class mission to Titan and Enceladus. There are multiple different avenues for implementing such collaboration, variously involving science team members, flight hardware including RPSs, launch vehicles and services, operations, deep space communications, and other aspects of a deep space mission. NASA/ESA collaborations are done on a no-funds-exchange basis, so implementation plans that involve either agency buying equipment or services from the other side of the Atlantic are not workable. Instead, any exchanges must be done on the basis of offsetting contributions, much like a barter system, and must be negotiated uniquely for each mission.

A brief summary of each agency's capabilities sets the framework for building a collaboration. NASA is technically capable of conducting every aspect of a Titan orbiter, montgolfière, and lander mission on its own, but the funding level needed outstrips what is expected for SMD in the anticipated time frame. For the anticipated funding level available, NASA can fly a very capable Titan orbiter (the objective of this study), but without *in situ* elements. ESA's capabilities closely mirror those of NASA in many important

respects, with a few notable exceptions. Currently ESA cannot provide RPSs or launch vehicles larger than their Ariane 5, and cannot launch any RPS from their prime launch site at Kourou, French Guiana (although that might change—see the ESA discussion in §G.1). With the L-class limit of 650M Euros cost to ESA, it is unlikely ESA could afford a capable orbiter mission to Titan with *in situ* elements, even with contributed RPSs, but the ESA assessment report in Appendix J indicates that they can design and fabricate a Titan montgolfière aerial vehicle and a lander. The highest value collaboration option with current capabilities and policies is to have a capable NASA Titan orbiter that delivers and supports ESA *in situ* elements, the primary arrangement postulated in the Ground Rules and Statement of Work for this study. An ESA montgolfière would necessarily be powered by a US-contributed MMRTG, and launch with a NASA launch vehicle from a US launch site would accommodate that and any other RPSs the mission requires. This arrangement keeps the number and complexity of NASA/ESA interfaces to a minimum.

The Cassini/Huygens mission is an example of a more elaborate collaboration arrangement. ESA and its Member States provided not only the Huygens *in situ* probe and support hardware, but also provided science instruments and other flight hardware for the Cassini orbiter. Science team members were shared across NASA/ESA boundaries as well. Items potentially available for consideration include science instruments and other flight hardware, operations and tracking services, science expertise, and even launch vehicles and services. Mission architectures that take advantage of such arrangements are discussed in §3.3.

H. NEXT THRUSTER TECHNOLOGY FOR TSSM SEP STAGE

H.1 NEXT Ion Thruster

The NEXT ion thruster exhibits excellent performance and life characteristics. An ongoing life test of a functional model NEXT thruster has demonstrated a propellant throughput of more than 350 kg and the thruster continues to run well. The proposed technology plan would significantly reduce the cost-risk of flying the NEXT ion thrusters on the Titan SEP Stage. The following activities are recommended for reducing this risk.

Recommended Cost-Risk Reduction Activities for the NEXT Ion Thruster:

1. Demonstrate repeatable fabrication of the ion accelerator system with an acceptable yield. Yield problems significantly impacted the fabrication of the flight ion thrusters for Dawn. The fabrication yield for the NEXT ion accelerator systems is currently unknown. This activity would identify the process steps in sufficient detail necessary to produce repeatable hardware.
2. Make the current life test a “test-to-failure,” i.e., continue the life test until the thruster fails. This activity is essential to determine the behavior of the thruster wear-out failure modes during the approach to failure. The information obtained from this will be used in models of the thruster life to quantify the thruster’s wear-out failure risk as a function of propellant throughput for a given mission profile.
3. Update structural and thermal models. Accurate structural and thermal models are essential for the flight implementation of the thrusters.
4. Redesign to eliminate molybdenum flux at angles ≥90 degrees from the thruster centerline. Eliminating the flux of molybdenum at large angles will significantly facilitate the integration of the ion thrusters with the SEP stage.
5. Redesign to incorporate features that enable easy installation/removal of hard and soft covers. Incorporating these features will significantly reduce the risk associated of working with and around the ion thrusters during the spacecraft assembly and launch operations.
6. Fabricate an EM thruster with the above modifications and use it in a second life test. A life test of a thruster fabricated by the flight thruster vendor is essential to make sure that any process-specific features are understood relative to their effect on the thruster life.
7. Perform cathode heater cycle test to low temperatures. No heater qualification testing to low temperatures has been performed to date. This testing is essential to make sure the heaters are qualified for the expected flight environment.

Desirable Cost-Risk Reduction Activities for the NEXT Ion Thruster:

1. Perform long-duration main-discharge-cathode and neutralizer-cathode life tests. Long duration cathode life testing is inexpensive because of the small test facilities required and is essential to verify the life margins for the cathodes. Models of the cathode life are very sensitive to the temperature of the electron emitter surface. Long-duration experimental data are required to validate and improve these models.
2. Investigate opportunities to reduce the amount of touch labor required for assembly.
3. Redesign to incorporate features that facilitate thruster handling. The intent of this activity is to make the thruster easier to be picked up and installed. This will reduce the risk of thruster damage during the spacecraft assembly process.
4. Redesign to place propellant feed line fittings in a convenient location for thruster installation. This change will reduce the time and risk associated with the thruster installation on the spacecraft.

H.2 PPU/DCIU

The NEXT project has designed, fabricated, and tested an Engineering Model (EM) PPU. This PPU has demonstrated the ability to operate the NEXT functional model ion thruster over the full throttle range. The ion propulsion system architecture identified for

the Titan SEP Stage requires that the control and telemetry features provided by the Digital Control & Interface Unit (DCIU) in the Dawn ion propulsion system be incorporated into the PPU rather than in a separate box. This architecture provides significant cost and risk benefits relative to the Dawn system. The following activities are recommended to complete the PPU development.

Recommended Cost-Risk Reduction Activities for the NEXT PPU:

1. Develop DCIU hardware board and software consistent with the xenon feed system (XFS) and PPU that can be incorporated into the PPU. The DCIU board in the PPU controls both the PPU operation and the part of the xenon feed system that provides propellant flow to the thruster being operated.
2. Redesign the PPU to accommodate the DCIU card to make a “smart” PPU.
3. Redesign beam current telemetry circuit to bring accuracy into spec.
4. Perform the required reliability analyses (FMECA, FMEA, EPSA, WCA, SEEA, thermal, and structural).
5. Perform thermal cycling and shock testing on redesigned EM unit.

Desirable Cost-Risk Reduction Activities for the NEXT PPU:

1. Redesign to eliminate output relays (to reduce mass and cost).
2. Redesign the PPU to improve manufacturability and reduce mass.
3. Incorporate self-test diagnostics for the PPU and thruster.

H.3 Xenon Feed System (XFS)

The NEXT Project has designed, fabricated, and tested a xenon feed system for the NEXT ion thruster. This XFS incorporates more features than are required by the Titan SEP Stage. The Titan SEP Stage team has defined an alternate technical approach that retains the technology validated in NEXT, while simplifying element of the system. Therefore, the following activities are recommended to reduce the cost and risk of implementing a flight version of the NEXT XFS.

Recommended Cost-Risk Reduction Activities for the NEXT XFS:

1. Eliminate thermal throttles from the Xenon Flow Controllers (XFC).
2. Replace the Mott flow control devices with viscojets. This change incorporates a lesson learned from Dawn, where the use of viscojets was found to be a significant improvement relative to the Mott flow control devices used on Deep Space 1.
3. Simplify and reduce cost of feed system cleanliness process. An improved process to meet the required point-of-use purity for the xenon propellant is essential for reducing the overall cost of the xenon feed system. There are good reasons to believe that the current vacuum-bakeout process used to assure the cleanliness of the xenon feed system is unnecessary and adds significant risk to the spacecraft processing. This task would demonstrate a lower-risk approach to achieving the same point-of-use purity for the xenon.
4. Further simplify the xenon feed system by tying the neutralizer-cathode and discharge-cathode flow branches together from the same proportional solenoid valve. This will reduce the number of components in the XFC, reducing cost and mass with no impact to the performance of the system for Titan.

H.4 Thruster-Gimbal

The NEXT Project has developed a functional model gimbal for the NEXT thruster. This gimbal, however, cannot be tested in a 1-g environment without significant ground support equipment to off-load the 1-g effects. This limitation would result in a significant cost and risk impact to the Titan SEP Stage integration and test program. Therefore, two parallel activities are essential to mitigate this risk:

1. Evaluate the use of the Dawn gimbal with the NEXT thruster. The Dawn gimbal design is such that it should easily accommodate the larger diameter of the NEXT thruster, but careful evaluation is required to identify what changes, if any, are necessary to accommodate the larger mass and higher power level of the NEXT thruster.

2. Evaluate the changes necessary to develop a 1-g version of the NEXT gimbal. Note, this activity is already underway as part of the ongoing NEXT Project. This item is included here to make sure that this evaluation is completed.

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I. IMPACT OF *IN SITU* ACCOMMODATION

The study Statement of Work includes the requirement:

The orbiter shall have the capability of delivering and supporting a Titan in situ vehicle(s) that is furnished by ESA as part of the collaborative program.

In developing both the Flight System and mission design for this study a number of areas have been affected by this requirement To this end, the NASA/ESA study team defined the *in situ* element resource needs and orbiter interface requirements that will lead to a smooth integration and enhanced mission science.

Science

The ability to carry one or more *in situ* elements to Titan has major implications on the science that can be performed. ESA has been an integral part of the TSSM JSDT from its inception, and the science goals of the orbiter and *in situ* elements have been closely integrated as they developed. While the JSDT has been guided by the requirement that the NASA-only orbiter mission should meet the Level 1 science objectives even without the ESA contribution, synergy with the investigations allowed by *in situ* platforms has been woven into the science planning in a way that would maximally enhance the science that could be addressed by the mission.

Mission Design

Accommodation of *in situ* delivery has a moderate impact on overall mission design. The primary impact is accommodation of the release of the *in situ* vehicles following Saturn orbit insertion (SOI). Mission design has included detailed analysis for targeting and release of two elements on consecutive post-SOI Titan flybys; a montgolfière, released on the first Titan flyby following Saturn arrival, and a lander released on the second flyby. These targeted releases introduce a perturbation in the Saturn Tour Phase of the mission in that the orbiter must be placed on a Titan impactor path, during which the *in situ* element releases occur. Following release, the orbiter must adjust its trajectory to ensure arrival at the optimum point for its Titan gravity assist and relay geometry. There is a ΔV penalty for this retargeting which is about 200 m/s for delivery at the times planned for this mission. An additional impact is the increase in mission operations activity required during this period, resulting in a somewhat higher level of staffing and tracking than would otherwise be the case.

Flight System

The orbiter Flight System has been designed with physical accommodation for two aeroshells (**Figure I-1**). A large aeroshell, 2.6 m diameter is accommodated on the +Y side of the spacecraft, and a smaller 1.8 m aeroshell is attached to the –Y side. Mass is included in the orbiter structures subsystem to account for the mounting hardware that would be provided for each aeroshell. A spin/eject device would be provided by ESA as part of their airborne probe support equipment.

Accommodation in other subsystems includes:

- C&DH provides two high speed serial bus (LVDS or RS-422) interfaces for pre-release communications
- Telecom accommodates post-release communications using existing orbiter telecom subsystem design (UST and HGA)
- Power provides 28 V electrical power prior to separation through dead-facing relays.

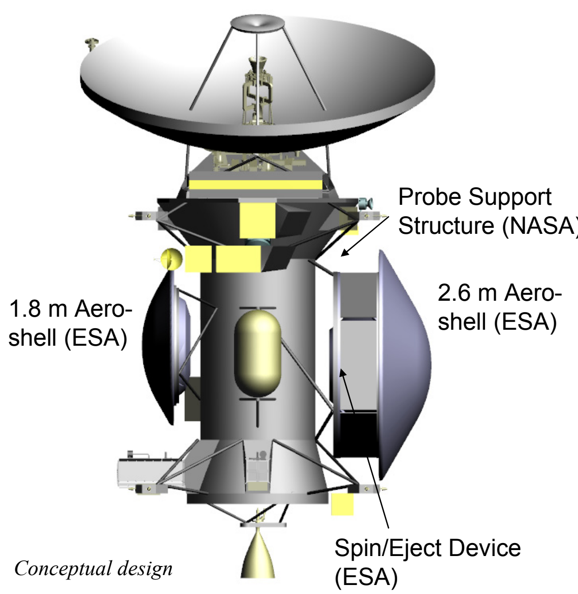

Figure I-1. *In situ accommodation envelope.*

Ground Operations

Ground operations would be impacted by the inclusion of the *in situ* elements in the launch processing flow at KSC, and especially important will be the integration of the MMRTG necessary for operation of the montgolfière. Care will be taken to ensure early coordination of ATLO activities between all mission partners. Incorporation of the NASA-provided RPS would be performed as late as practical in the flow and would be preceded by a rigorous validation of integration procedures through the "trailblazer" activities.

Launch Vehicle

One potential difference between a mission with and without *in situ* accommodation is the launch vehicle. Elimination of the additional launch mass represented by the *in situ* element and its accommodation hardware would enable the orbiter to move from an Atlas V 551 to an Atlas V 521 launch vehicle with no increase in flight time. Alternatively, the extra mass margin introduced by the absence of the *in situ* elements could be used to re-optimize the mission to shorten cruise duration.

RPS Provision

Accommodation of the *in situ* elements brings with it the requirement to provide RPS assets to the ESA montgolfière. Costs of this RPS provision must be accounted for in the NASA costs.

Cost Impact of In Situ Accommodation

Costs associated with accommodation of the ESA-provided *in situ* elements were included in the Baseline mission cost estimates generated for each affected WBS element. These costs are presented in **Table I-1**. Subtracting the costs associated with the accommodation indicates a savings of $119 M (RY) between the NASA/ESA Baseline and NASA-only missions. This represents the incremental cost impact to NASA resulting from accommodation of the ESA *in situ* elements.

Table I-1. *In situ accommodation cost impact.*

WBS Element	NASA/ESA Baseline ($M RY)	NASA-only Mission ($M RY)	Accommodation Cost
01 Project Mgmt	183	182	1
02 Project Sys Eng'g	60	58	2
03 Safety & Mission Assur	101	101	-
04 Science	295	295	-
05 Payload System	297	297	-
06 Spacecraft System	805	775	29
07 Mission Ops Sys	424	424	-
09 Ground Data System	99	99	-
10 Project Sys I&T	67	67	-
11 E/PO	22	22	-
12 Mission Design	29	29	-
CBE Cost	2,381	2,349	32
Reserves	734	708	26
CBE + Reserves	3,115	3,057	59
06A.17 Orbiter RPS	153	153	-
06C Lander RPS	2	-	2
06D Balloon RPS	59	-	59
DSN Aperture	111	111	-
Launch System	268	268	-
Total Mission Cost	**3,708**	**3,589**	**119**

J. EUROPEAN SPACE AGENCY *IN SITU* CONCEPT IMPLEMENTATION

The European Space Agency (ESA) Assessment report describing the Titan Saturn System Mission (TSSM) *in situ* element concept implementation is publicly released separately by ESA.

ESA-SRE(2008)4

TSSM IN SITU ELEMENTS

ESA Contribution to the
Titan Saturn System Mission

Assessment Study Report

European Space Agency
Agence spatiale européenne

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K. MISSION OPERATIONS LESSONS LEARNED STUDY

This appendix includes a traceability matrix indicating TSSM responses to lessons learned and the report on Mission Operations Lessons Learned for the Next Outer Planets Flagship Mission.

Mission Operations Lessons Learned Applied to TSSM

Table K-1. *Traceability between the lessons learned as described in the report Mission Operations Lesson Learned Study for the Next Outer Planets Flagship Mission and specific responses taken by TSSM. Although specific references are called out in this table, many of these lessons learned are further discussed throughout the report.*

Category	Lesson Learned	TSSM Report Section*	Description of TSSM Reponses to Lessons Learned
Mission Design / Architecture	Minimizing the amount of cruise science required of the operation including that opportunistic science taken during gravity assist maneuvers. However one can not discount the benefit of using these operations to train the team and test systems for eventual prime science operations.	§4.6	TSSM is focused on Titan and Saturn System science in as much as it informs us about Titan. During cruise, there are no planned science observations. There are planned and budgeted calibration events that will also benefit TSSM by training the team for primary science operations. Opportunistic science is a possibility during the Saturn Tour Phase, but is not a cost driver in the current implementation.
Management & Organization	Reduce the complexity of the contention resolution process by choosing a single PI's. Streamline the arbitration process so that it need not involve the majority of the mission planners. A strong "super PI" or Project Scientist could oversee this process.	§4.6.2	During the 20 month orbital phase, the spacecraft will collect data continuously according to a pre-defined, cyclic observation scheme, alternating between already-selected instrument suites. This simplification of operations avoids the conflicts experienced by earlier missions. Further, the selection of which instruments are in operation for each Enceladus flyby has been made apriori. Furthermore, the dual-axis, steerable HGA decouples data collection from communications. TSSM's tightly focused payload reduces the complexity of "contention resolution" and will result in more efficient operations.
	Co-locate mission planners or have representatives with decision making capability co-located to help reduce communications delays when iterating on plans.		
	Investigate ways to streamline the ITAR/TAA processes for working with foreign instrument teams/individuals.	§4.11.3	TSSM already has a TAA in place for collaboration with ESA, CNES and non-US Science Team Members. This will be continually maintained throughout the project lifecycle.
Flight System Interfaces	Evaluate operational complexity and incorporate ease-of-use features for each primary flight system with special emphasis on G&C and C&DH flight processor interfaces as they are typically the most complex.	§4.11.7 §4.4.3	Ease of use was considered in all aspects of the TSSM concept starting with the mission design going all the way through the flight and ground elements. The diverse team that developed TSSM has considerable experience building and operating ongoing missions to Mars, Mercury, Jupiter and Saturn. Lessons learned and relevant experience have been applied to the design of flight hardware and flight/ground software elements to ensure operability. Furthermore, a considerable amount of personnel have been scheduled and funded to work MOPs and GDS in Phases A and B. The project will ensure close coordination between Project Engineering, Spacecraft Engineering and Operations.
	As part of the next OPF mission design effort, formalize a joint operations and flight system design process for each proposed flight system to evaluate its design in terms of operability and quantify affect on total mission costs. Note: This process was ad-hoc on past missions and subject to the availability and capability of the specific operations team involved in the early stages.		
	Consider such features as: coupled thrusters, automated momentum management, scan or gimbaled platforms that can significantly reduce conflicts between instrument types (fields and particles vs. pointing) or between payload and communications system, deterministic slew paths, ephemeris based pointing.	§4.4.3,	All of these Lessons Learned have been incorporated into design of the orbiter: coupled thrusters; 2-axis gimbaled antenna; co-alignment of related instruments and complementary alignment of nadir and off-nadir instruments.

Category	Lesson Learned	TSSM Report Section*	Description of TSSM Reponses to Lessons Learned
Flight System Interfaces	Ensure adequate power margins and consider predefined payload modes/configurations to simplify planning. Favor power over mass in use of PMD's, coupled thrusters, proper instrumentation.	§4.4.2.9	TSSM power budget includes more than the 33% margin stated in the study ground rules. Because of the way this reserve is calculated per JPL Design Principles, this equates to 49% on current best estimates. During the 20 month orbital phase, the spacecraft will collect data continuously according to a pre-defined, cyclic observation scheme, alternating between already-selected instrument suites. This simplification of operations avoids the conflicts experienced by earlier missions. Further, the selection of which instruments are in operation for each Enceladus flyby has been made apriori. TSSM's tightly focused payload reduces the complexity of "contention resolution" and will result in more efficient operations. TSSM uses coupled thrusters and decoupled high gain antenna.
	Incorporate a file system and pre-allocated (by ground rules) SSR space. Sufficient margins for command and SSR memory. Use automated file playback software and CFDP to minimize SSR management and to have automated retransmission for data dropouts. Consider CFDP for command uploads and potential use for telemetry.	§4.4.3.8	The TSSM system software utilizes all of the tools recommended by this Lesson Learned. The SSR has margins required by JPL Design Principles.
	Strive for commonality in payload instrument telemetry and command interfaces.	§4.4.3.5, Phase A	TSSM would use a common telemetry and command dictionary for the instruments which would be specified in the AO process. For hardware interfaces, TSSM has baselined SpaceWire for a common instrument interface to high data-rate instruments and the RSB for low data-rate instruments.
Science/ Mission Operations	Incorporate a planning process that is efficient enough for Titan orbital operations, and modify as necessary for tour operations. Consider cost constraining planning tools (i.e., market based and priority based systems).	§4.6.2	During the 20 month orbital phase, the spacecraft will collect data continuously according to a pre-defined, cyclic observation scheme, alternating between already-selected instrument suites. This simplification of operations avoids the conflicts experienced by earlier missions. The TSSM observation scheme, developed by the Operations Lead and approved by the Titan Joint Science Definition Team, will minimize the need for continuous re-planning.
	Develop process that minimizes the number of planning iterations, bounds time allocated to planning each significant event, and incorporates the principle of "good enough".		
	Develop an integrated planning and sequencing tool based on model-based engineering and state analysis that would be used throughout the project lifecycle.	§4.8	Evaluation of Model Based Engineering for use during Mission Operations is included in list of activities for Pre-Phase A and Phase A.
Ground System Interfaces	Incorporate information management systems (i.e., CIMS) for entire team's remote access to planning products, telemetry, command sequences, and action item tracking.	§4.5.2.2	The Mission Operations System design and implementation includes a rich online collaboration system to support remote planning and operations support.
	Have a PI set priorities. Have ground system and planners implement those priorities and optimize supporting processes as needed.	§2.3, §2.4	The Project Scientist will set the priorities in working with the Project Science Steering Group. The Project System Engineer and Science System Engineer are funded in the baseline budget through Phase E to ensure that the priorities are implemented efficiently.
	Incorporate resource modeling and flight constraint models early in the planning process for early identification of problems. Permit science planners access to models of similar fidelity as what MOC uses for end validation. Make accessible to distributed team.	§4.5	MOS includes extra staffing starting in phase A to develop mission models for working out operational issues, support planning, and practice flying the spacecraft. These tools will evolve to incorporate updated models (e.g., ACS and Power models) used in flying TSSM. These models will be made available and used by all teams to ensure everybody is working with the same model.
	Incorporation of flight system faster than real-time software models for resource and constraints checking (i.e., SoftSim or Statesim).	§4.4.6	A high fidelity model-based flight software simulation capability (S-Sim) is funded in the baseline budget for the mission.

Category	Lesson Learned	TSSM Report Section*	Description of TSSM Reponses to Lessons Learned
Ground System Interfaces	Adoption of unattended pass operations for non command passes. Limit number of command passes. Rely on automated limits and alarms checking versus manual, by FC or ACE. Unattended (automatic) radiation of non critical commands	Phase A	It is the intention of TSSM to use unattended pass operations approach during non command passes. Automatic radiation of non critical protocol commands will be studied in Phase A.
	Streamlined process for late knowledge updates including ephemeris and time shifts.	§4.6	This issue has little impact on TSSM because our science collection architecture is designed to not require quick turn-around or replanning between successive observations.
	Consider incorporating real-time automated assessment tools and post event trending tools (i.e., MRO).	§4.11, §4.5	TSSM will implement the best proven operational tools available at the time, leveraging those previously used on past missions in a cost effective manner.
Testing and Evaluation	Adopt logical testing steps with software tools catching problems upstream (with faster than real-time software) of more sophisticated (real-time hardware) simulations downstream.	§4.4.6	A high fidelity model-based flight software simulation capability (S-Sim) is funded in the baseline budget for the mission. This software tool will be used to head off problems early in mission software and command sequence development.
	Incorporate software tools, scripts, to aid in H/W simulator setup and configuration control using planning system inputs for starting conditions. Use checkpoint and restart process for H/W simulations.	§4.4.6	The simulation environment interfaces and procedures will be compatible with those of the hardware testbeds. Checkpointing and restart processes are included in the simulation environment.
	Automate syncing of S/W sim (and H/W sim tools) with flight for proper configuration control. Perform periodic audits.	§4.4.6, Phase A	Automation and configuration control will be included in the software development environment to maintain synchronization of software and hardware simulations. Further work on this is deferred to Phase A.
	Incorporate tools for post simulation data processing and distribution - reduce labor and time requirements.		
	For geographically distributed team members, provide easy access to data for each reviewer. (i.e., MRO has web based results outside flight ops network)	§4.5.2.2, Phase A	TSSM will implement the best proven practices available at the time, leveraging those previously used on past missions (e.g., Cassini, MESSENGER, New Horizons, and MRO) in a cost effective manner. The Mission Operations System design and implementation includes a rich online collaboration system to support remote planning and operations support. Further work on this is deferred to Phase A.
	Have good validation of software simulators so they can be used in place of hardware simulators. Incorporate fidelity into software models match hardware simulations as closely (and quickly) as possible.	§4.4.6	A high fidelity model-based flight software simulation capability (S-Sim) is funded in the baseline budget for the mission. This software tool will be used to work out problems early in command sequence development. Critical events, first-time events and mission troubleshooting will be executed on real-time hardware-in-the-loop simulators to ensure mission success.
	Use real-time simulators by exception (only as needed), faster than real-time software for all nominal operations. Ensure adequate numbers and fidelity of real-time hardware simulators during each phase of the mission.		

K.1 Mission Operations Lessons Learned Study for the Next Outer Planets Flagship Mission (OPFM)

K.1.1 Executive Summary K-5
K.1.2 Introduction K-6
K.1.3 Mission Operations and Ground Data System Cost Drivers K-7
K.1.4 MO & GDS Staffing and Comparisons K-20
K.1.5 Recommendations for Reducing Flagship Phase E Costs K-28
K.1.6 Acknowledgements K-30

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K.1.1 Executive Summary

As an effort to reduce operations costs associated with the next Outer Planets Flagship Mission (OPFM), Jet Propulsion Laboratory (JPL) tasked the Johns Hopkins University Applied Physics Laboratory (JHU/APL) to lead a study of the Cassini mission operation cost drivers and those of other planetary space missions, including two missions currently operated at APL, MESSENGER and New Horizons, and JPL's Mars Reconnaissance Orbiter.

The study team derived a comprehensive list of space mission operations costs drivers and through the evaluation of each mission and found the following to be the top cost drivers:

a. Mission architecture: Includes mission trajectory, type, duration, number of flybys or gravity assist maneuvers.
b. Management and project organization: Considers organization structure, geographical boundaries, and organization conduct.
c. Flight system interfaces:

   Systems: Includes number of flight vehicles, system redundancy, complexity of fault protection systems, number of engineering calibrations.

   Guidance and control system design: sensors, actuators, control modes, pointing constraints and accuracy, momentum management scheme, number of tunable parameters, articulating mechanisms.

   Command and data handling: Number of fight software applications, stored command management or scripting capabilities, type of data recorder, data storage margin, memory margin for commands, number of tunable parameters, data identification and tracking.

   Payload: Number and type of instruments, degree to which instrument processor interfaces and capability, number of instrument mechanisms.
d. Science operations: Includes science mission duration, science team structure, number of interfaces between instrument teams, number and density of science observations, type of observations, level of post launch science operations development, instrument data volume, data latency requirements, number of instrument and calibration and maintenance operations, data quality requirements.

Each of the missions studied were characterized for their relative complexity in each of the above major categories and other minor ones, and compared against the actual (or planned, where applicable) staffing levels of each mission at key mission phases. The results of this analysis are charted in **Figure K.1-1**.

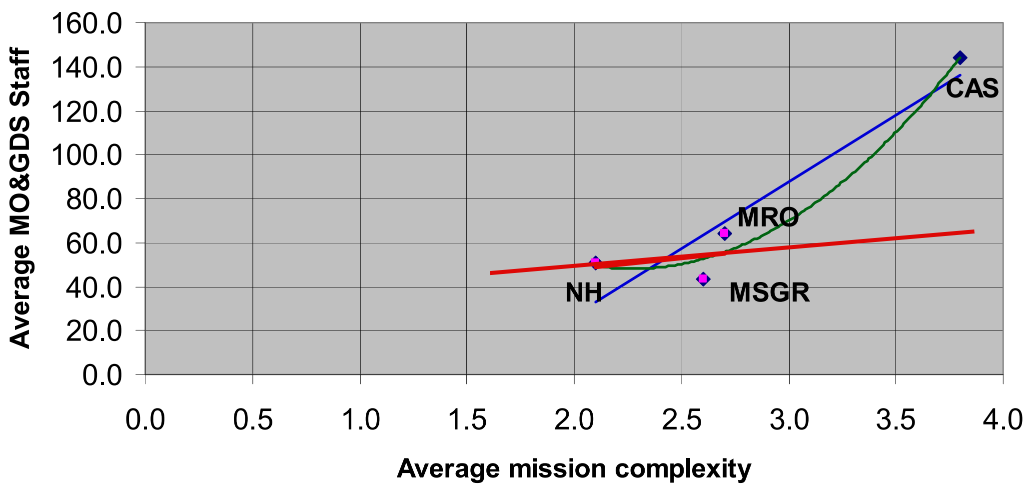

Figure K.1-1. *Mission ops team size vs. average mission complexity.*

This plot shows New Horizons, MRO, and MESSENGER are relatively near each other on the complexity vs. cost grid, while Cassini is in a region on its own in terms of both complexity and cost. A least squares fit of the four data points is shown as a blue line, the green line an exponential fit. Both CAS and NH are above the linear fit while MSGR and MRO are both below it indicating they may be the most efficient of the four operations. MESSENGER falls the furthest below.

A least squares fit of the MRO, MESSENGER, and New Horizons data points is shown as the red line. While one would not expect a simple linear increase in cost as complexity rises significantly (complexity across systems can have a compounding affect) it can serve as a guide for the lower bound of the expected cost increase. Conversely, the exponential fit to actual costs, including Cassini (green line) can serve as an upper bound for expected operations cost.

The study's most valuable end product is the numerous, tangible recommendations for reducing the cost and complexity for future space operations, including the next OPF. Recommendations are described in detail in §K.1.5 and organized by cost driver categories:

- Mission Design/Architecture
- Management and Organization
- Flight Systems Interfaces
- Science Operations
- Ground System Interfaces
- Testing and Validation

Many are based on successful approaches utilized on the missions under study. Application of those recommendations to the development and operations phases will permit future operations to be conducted in a significantly more efficient manner.

K.1.2 Introduction

In December 2007, NASA's Planetary Science Division announced its intent to conduct Phase-2 studies for the next OPFM. JPL held the overall responsibility to conduct the associated OPF Phase-2 studies for Titan and Europa destined missions. One of the several tasks identified in the Statement of Work from NASA was to perform a Mission Operations Lessons Learned Study (referred to here on as the LL Study) with special focus on Phase E cost drivers and operations. The intent of the LL Study was to safely lower Phase E operations costs from those traditional to this class of mission. Mark Holdridge (APL) led the study with a team formed from several institutions, including APL, JPL, and ARC. Consequently, a LL Study was kicked-off in late February 2008 and given the following task:

> *"Capture relevant lessons learned from the past and present operational missions, including Cassini, in the area of Phase E cost drivers and operations. Document the collective experience base of both APL and JPL from a variety of missions conducted by the two Centers that covers a spectrum of mission complexity and implementation modes such as Cassini, MESSENGER, STEREO, New Horizon and MRO . Examine the implementation approach of relevant missions in the areas of GDS, MOS, Science Operations Systems, and flight/ground functionality and performance allocation. Identify the cost drivers and assess related risk postures. Provide briefing to the MOS/GDS/Science Center task of the EJSM and TSSM OPF teams in those areas addressing cost, performance and risk and recommendations for approaches to minimizing cost. Document results in a written report. Provide write-up to the final Mission Concept Report"*

The joint JPL/APL/ARC study team consisted of experienced deep space mission planners, operations leads, and analysts knowledgeable of APL's planetary mission operations and of JPL's Cassini and Mars Reconnaissance Orbiter (MRO) operations processes; where additional information was needed, the LL study team sought it from the mission team. The study proceeded with the following subtasks identified to reach the goals of the study:

Study Plan

1. Develop a set of space mission operations cost drivers and organize into major categories and subcategories
2. For each cost driver category, define measurables that can be used to assess the degree to which each driver affects

each operation. Define any supplemental information also needed to characterize each mission.

3. Interview each operation under study (Cassini, MRO, New Horizons, and MESSENGER) and obtain metrics and supporting information that characterize each operation and measure its complexity or difficulty level related to each cost driver and to each other.
4. Compile MO&GDS staffing levels for each mission, pre- and post-launch, by similar WBS elements.
5. Data Analysis and recommendations.
   - 5.1. Review all mission characteristics and compare and contrast each operation in terms of relative complexity and associated cost (staffing)
   - 5.2. Identify those cost drivers that had the most affect on each operation.
   - 5.3. Develop a set of recommendations designed to lower total mission operations (and total mission) costs for next OPF mission.

Despite being included in the task statement, time and resource limitations precluded the team assessing relative risk postures and comparisons of each missions risk stance. While this alone did not affect identification of efficient operations techniques, it prohibited qualifying actual mission costs in terms of its risk stance.

It should be noted that many of the individuals supporting the LL Study have also worked on the missions under study (expediting the data collection process) and some were serving in systems engineering related capacities on the either or both the Titan or Europa OPF study teams, thereby facilitating the transfer of lessons learned to the respective design efforts.

K.1.3 Mission Operations and Ground Data System Cost Drivers

The LL Study Team formulated a list of major categories of space mission cost drivers and expanded each to formulate a complete criteria by which operations can be evaluated and relative complexities assessed.

A summary of the major cost drivers identified and associated measurables are included below. Each operation was assessed individually using these criteria.

a. Mission architecture: Includes mission trajectory, type, duration, number of flybys or gravity assist maneuvers.

b. Management and project organization: Considers organization structure, geographical boundaries, organization conduct.

c. Flight system interfaces:
   - *Systems*: Includes number of flight vehicles, system redundancy, complexity of fault protection systems, number of engineering calibrations. Also includes operations complexity of each spacecraft subsystem.
   - *Guidance and Control System Design*: sensors, actuators, control modes, pointing constraints and accuracy, momentum management scheme, number of tunable parameters, articulating mechanisms.
   - *Power System Design*: power system margin, energy management complexity, power generation (solar vs. nuclear).
   - *Propulsion System Design*: propellant margins, operations constraints limitations, propulsion type (mono, bi-prop, hybrid, Ion), couple vs. decoupled thrusters.
   - *Thermal System Design*: number of thermal constraints to be managed by operations team, level of onboard thermal control automation, special data analysis or planning tools required.
   - *Command and data handling:* Number of flight software applications, stored command management or scripting capabilities, type of data recorder (volatile vs. non-volatile, use of file system or other onboard data management techniques, including CFDP), data storage margin, memory margin for commands, number

of tunable parameters, data identification and tracking.

- *Communications:* Downlink bandwidth requirements and overall margins, number of supported data rates, ability to add new data rates in phase E, relay or multi-vehicle communications, fixed or gamble antennas, radiometric tracking requirements.
- *Payload:* Number and type of instruments, degree to which instrument processor interfaces and capability vary, number of instrument mechanisms.

d. Science operations: Includes science mission duration, science team structure, number of interfaces between instrument teams, number and density of science observations, type of observations, level of post launch science operations development, instrument data volume, data latency requirements, number of instrument and calibration and maintenance operations, data quality requirements.

e. Ground systems interfaces: Sizing of S/W maintenance and enhancement effort, centralized or distributed data processing and distribution centers, standard vs. specialized data products, heritage of ground system, hardware simulator number and fidelity, number and type of workstations,

- *Mission planning:* Level of automation and special S/W tools, number and type of flight constraints, resource constraints and margin availability, level of command block reuse, onboard sequencing capabilities (use of onboard macros, event driven commanding …), command sequence planning process and number of iterations.
- *Mission control:* Level of automation of real-time flight control operations for both assessment and commanding functions, density of DSN supports required, number of contingencies to plan for.
- *Mission assessment:* Level of automation of trending and assessment tools, data trending and review requirements.

f. Testing and validation: Includes ease of systems to validate command sequences early in sequence development process, level of scripting or automation in configuring and operating test environment and assessing test results. Extent to which real-time (hardware) simulators used vs. faster than real-time (software) simulators.

Separate evaluations of each mission's complexity relative to the above cost drivers can be found in the upcoming sections.

K.1.3.1 MRO Mission Summary and Primary Cost Drivers

K.1.3.1.1 Mission Summary

The Mars Reconnaissance Orbiter (MRO) was launched on August 12, 2005 on an Atlas V401 launch vehicle from Cape Canaveral Air Force Station and arrived at Mars on March 10, 2006. MRO carries a rich set of science instruments to Mars to survey the global and regional aspects of mars in addition to special targeted observations. There is also a set of engineering instruments providing optical navigation, Ka-band telecommunication and ultra-high frequency (UHF) relay services.

After a seven-month interplanetary cruise, MRO was captured into a 35.5-hour orbit around Mars. On March 23, 2006 MRO began its aerobraking phase and reduced its orbital time to less than two hours to reach the desired ascending node time of 3:00 pm Mars Local Time. Due to its orbit geometry and science requirements, the MRO aerobraking period involved 5 months of highly intensive operations period.

In August 2006 after successfully completing the aerobraking phase, a set of maneuvers were conducted to finalize the Primary Science Orbit (PSO). A set of transition activities were carried out, including engineering and science instrument calibrations and a weeks worth of "science practice" just prior to solar conjunction. During the 2-year primary science phase MRO will return at least 34 Tb of science data and a maximum of over 200 Mb per day. MRO will collect most of its science data in a constant nadir pointing mode, however, high

resolution targeted data at angles of up to 30 deg off-nadir will be collected up to twice per orbit.

K.1.3.1.2 MRO Primary Cost Drivers

Management and Project Organization

The MRO team is comprised of six organizations: JPL (which manages MRO), Lockheed Martin Space Systems, Applied Physics Lab, University of Arizona, Malin Space Science System, and the Italian Space Agency (ASI). Together this comprises a total of twelve teams during the post-launch phase. The majority of mission operations teams are co-located at JPL and at LMSS in Denver, Colorado. Science operations teams are located throughout the country and with the cooperation of ASI.

Some orbiter mission operations team members, tools and services are shared across projects in a multi-mission organization located at both JPL and LMSS. This sharing of infrastructure and workforce offsets potential cost increases due to distributed operations.

Orbital operations requirements translated into two parallel teams where one worked on the three-shift a day aerobraking operations and the other worked on the planning, development and testing activities.

Flight System Interfaces

The MRO spacecraft is single fault tolerant with most orbiter subsystems block redundant and cross-strapped. Attitude control is 3-axis stabilized with high precision pointing and fully gimbaled solar arrays and high gain antenna. The flight computer is a RAD 750 flight processor with ample memory resources and high throughput components for a throughput margin of ~70%. A series of on-board software constraints and compression and formatting processes assure high throughput rates and isolation of instrument command and flight software errors to single instrument data streams. The science data collected is stored in the 160 Gb on-board solid state recorder (SSR). The SSR is formatted as a high speed raw data input buffer and a large storage location for formatted data awaiting downlink.

MRO communicates with Earth via the DSN at a large variety of rates up to 6 Mbps and utilizes either Reed-Solomon or Turbo encoding schemes. MRO downlink also utilizes the CCSDS File Delivery Protocol (CFDP) to help identify data gaps and facilitate retransmission if needed. With the current Deep Space Network (DSN) contact schedule of 19 eight-hour tracks per week, the Baseline mission plan is for MRO to return 34 Tb of raw science data during the two-year primary science phase.

Eight scientific and two engineering investigations were selected by NASA. Four science investigations are led by Principal Investigators (PI) with PI provided instruments, two use facility instruments and have appointed team leads, and two are investigations led by PIs that make use of engineering systems on the orbiter. In addition, two engineering demonstrations, led by PIs and a UHF relay radio system are included as payloads.

The payloads are:

- Mars Color Imager (MARCI)—PI provided
- Mars Climate Sounder (MCS)—PI provided
- High Resolution Imaging Science Experiment (HiRISE)—PI provided
- Compact Reconnaissance Imaging Spectrometer for Mars (CRISM)—PI provided
- Context Imager, (CTX)—facility instrument with appointed team lead
- Shallow (Subsurface) Radar, (SHARAD)—The Italian Space Agency (ASI) provided this facility instrument. The SHARAD investigation team includes members from both ASI and NASA.
- Gravity Science Investigation—PI led, uses orbiter telecom system
- Atmospheric Structure Facility Investigation—PI led using accelerometers and other orbiter telemetry during aerobraking.
- Optical Navigation (Camera)—PI led, operated during cruise phase only
- Ka-band Telecommunication demonstration—PI led, demonstrated in cruise phase, partial failure prevents prime mission operations
- Electra, UHF communications and navigation package—operated by orbiter operations teams in support of Mars surface missions.

Ground Systems Interfaces

The MRO ground system functions are provided by the following organizations:

- Deep Space Network—DSN provides the data capture and command delivery functions. Data capture functions include not only the traditional telemetry processing such as frame sync and packet extraction but also the CFDP processing.
- Multi-mission Ground System Services—MGSS provides telemetry display and channel processing, sequence generation and science data server for raw data distribution, and navigation software.
- MRO project—MRO provides facilities at JPL and LMSS. These include unique science target planning software, spacecraft performance and analysis software; and multi-mission software adapted to support MRO ATLO activities. In addition, MRO provides hardware procurement and installation, and integration of the software and hardware into an operable system.
- Science teams—Each science team provides facilities, software, and hardware for their own command generation and standard and special data processing.

Mission Operations

The MRO mission operations system (including the ground data system) is developed and managed by JPL across the distributed organizations. During the development phase the Mission Operations System provides: system engineering, including both MOS and GDS system engineering functions and coordination of the flight teams and data system development activities; MOS team development for all the flight and science teams during phase E; and data system development functions in support of flight and science team needs

During the operations phase the organization is structured into teams which cover all aspects of a flight project. Teams include the Flight Engineering Team (at both JPL and LMSS), Mission Planning and Sequencing Team, Navigation team, Science Operations Teams (at JPL and remote sites), and the Ground Data System team. Additionally, a Chief Engineer is appointed to coordinate all system engineering operations as well as lead anomaly responses.

Science Operations

During the Primary Science Phase (PSP), the MRO operations teams were presented with two major challenges—unprecedented high data rate and data volumes, and complex science planning and resource sharing. Each of the science instruments had its unique requirements for global mapping, regional survey, and targeted observations. Some instruments preferred nadir-only observations, while others required off-nadir observations (especially for stereo viewing). The requirements from these instruments presented a significant challenge for the design of a complex science planning and resource allocation process. In addition, because of the high resolution instruments, the process for maintaining required navigation accuracy was challenging.

MRO science operations are conducted in two parts. The teams, either individually or in cooperation with other teams, select their off nadir and coordinated target observations. The Payload Operations Support Team at JPL, following predefined procedures, integrates the science team observation requests to produce a combined and conflict free list of targets. The target list is uplinked to the orbiter for ephemeris based timing and pointing execution. Each instrument team provides all of its own command sequences and routes them to the orbiter via automated uplink processes. The teams use their remaining observation time and data resources to build non-targeted, nadir based observation sequences that are sent to the orbiter as needed.

Cost Driver/Mitigators Summary

- Complex resource allocation for pointing and data volume is a significant driver mitigated by on-board ephemeris based timing and pointing, and by centralized coordination and allocation of pointing and data resources.
- Extremely large data volumes drive cost by allowing large numbers of observations by a large and complex payload and by the need for high volume data processing and distribution systems.
- The large numbers of observations are mitigated by the allocation and coordination processes.
- The data processing and distribution costs remain high but are mitigated in part by common raw data distribution methods and legacy systems for some instruments.

K.1.3.2 Cassini Mission Summary and Primary Cost Drivers

K.1.3.2.1 Mission Summary

The Cassini mission to Saturn, a joint endeavor of NASA, the European Space Agency and the Italian Space Agency is a flagship mission to orbit the Saturnian system carrying a diverse set of 12 science investigations. Also onboard Cassini is a scientific probe called Huygens that was released from the main spacecraft to parachute through the atmosphere to the surface of Saturn's largest and most interesting moon, Titan, which is shrouded by an opaque atmosphere. Titan's atmosphere includes organic compounds leading scientists to believe that the moon may be like a frozen vault of conditions similar to those on Earth before life began. The Cassini orbiter also uses imaging radar to map Titan's surface.

Launched in 1997, Cassini's interplanetary trajectory took 7 years to reach Saturn, including two gravity assists from Venus and one from Earth. The prime mission of 4 years included 45 encounters with Titan, 9 with icy satellites, 74 Saturn periapses as well ring crossings. The extended mission, which will be starting in 2009, will provide additional flybys of Titan (26), icy satellites (9), and Saturn periapsis and ring crossings (59).

K.1.3.2.2 Cassini Primary Cost Drivers

It should be recognized that Cassini, as a flagship mission, is the most complex mission architecture out of the four studied. The in-situ ESA Probe accommodation, multiple of flybys and ring crossings and duration of the science mission is significantly more operationally demanding than the other missions being analyzed in this study.

Management and Project Organization

The Cassini management is co-located at JPL, with eight remote science team participating, including one international one. Details of the various remote operations sites are listed in the *Science Operations* section below. Since Cassini is a directed flagship mission, the science investigations were selected via NASA AO. There are 12 instrument PIs and interdisciplinary science investigations. They each have specific mission objectives to meet but need to work closely together given the interactive nature of the operations. This requires extensive meetings to agree on negotiated activities and priorities for each event.

The operations teams include Spacecraft Operations (SCO), Navigation, Science & Uplink (SP and ULO) and Mission Support & Services (MSS). There is no mission manager; the team chiefs carry those responsibilities.

Finally, having a large budget encouraged doing many new things to improve the GDS and project development process that usually translated into greater costs. The larger budget also drove a need to have greater oversight that has its own increased cost.

Flight System Interfaces

Cassini is a three-axis stabilized spacecraft outfitted with 12 diverse science investigations. The instruments often have multiple functions, equipped to thoroughly investigate all the important elements of the Saturnian system. Cassini's remote sensing instruments provide data for global studies of Saturn's atmospheric temperatures, clouds, and composition, as well as studies of Saturn's rings and its many natural satellites.

The spacecraft communicates through body-fixed antennas: one high-gain and two low-gain, and is powered by three Radioisotope Thermoelectric Generators (RTGs) providing ~700 W at the end of prime mission. The Attitude Control Subsystem (ACS) uses three Inertial Reference Units (IRUs) and a Stellar Reference Unit (SRU), or star tracker, to determine both the spacecraft's position and orientation. Reaction Wheel Assemblies (RWAs) are one of the two systems used to provide pointing control of the spacecraft in flight (with the thrusters of the Propulsion Module Subsystem as the other). The thrusters, along with a main engine, also perform orbit trim maneuvers (OTMs) to keep Cassini following the chosen trajectory around Saturn.

The science instruments are all body-mounted; a scan platform was deleted as a cost-saving measure during spacecraft design and integration. Thus the entire spacecraft must be rotated for any one instrument to achieve a desired pointing attitude, and also to point the high gain antenna at Earth for communications. Data taken by the instruments is stored on two solid-state recorders (SSR), with a total capacity of 4.6 gigabits. The spacecraft

utilizes the Deep Space Network to downlink, on average, over one gigabit of data daily.

Several significant design features drive Cassini's operations cost. Some of these are unique to the mission and the circumstance of the mission, but some are lessons that are applicable to future missions, such as the Outer Planets Flagship mission. This summary will highlight both.

The spacecraft was not designed for maximum operability. One of the key design cost drivers on Cassini is the fact that all 12 of the instruments and high gain antenna are body fixed. While some of the collaborating instruments are mounted to observe simultaneously (for example, the optical remote sensing [ORS] instruments are co-boresighted, along with the Radar), there are still the fields and particle instruments that require different look directions and the HGA that needs to point toward Earth during daily downlink DSN passes. In addition, the ORS observations also require scan modes and mosaics by spacecraft pointing that conflict with each other.

Further complicating the already involved planning for spacecraft pointing, the reaction wheel usage for each science observation activity must be analyzed by special tools for potential RWA degradation, and steps in the planning process have been added for the turn profiling evaluation. That analysis feeds back into the observation design, which is then reworked with the science planning teams as necessary in order to maintain a sustainable science and engineering performance.

Another design impact on operations has been the uncoupled thrusters. Every time thrusters are fired, including the routine RWA unloadings, the Navigation team has to model and measure the resulting ΔV in its orbit determination. Again, special analysis tools and steps in operations have been developed to accommodate this design implementation. Unplanned ΔV increases the Navigation Team's workload.

The 2.3 Gb mass memory storage element, a solid-state recorder, does not have a file system. Science data accounting was labor intensive due to the memory architecture (which was typical of the architectures of the time for spacecraft). While this design feature has not significantly increased the size of the team, the data management on Cassini complicates the operations and adds to the process of planning and integrating a sequence.

Science Operations

On a typical day in the Cassini tour, the spacecraft collects science data for 15 hours by orienting the spacecraft at a variety of targets. One instrument at a time dictates the pointing of the spacecraft, and other instruments may "ride along" and collect data at the same time. Collaborative data collection is often negotiated between the science teams. The remaining 9 hours is spent in one block on Earth-point, downlinking the data. Control of the spacecraft is done, for the most part, from autonomous sequences stored onboard the spacecraft. Spacecraft sequencing uses a combination of centralized commands (for control of the system level resources) and instrument commands to conduct activities and maintain the health and safety of the spacecraft. The spacecraft is flown with sufficient margins to allow the instruments to operate fairly independently from each other, and with a minimum of real-time ground intervention.

The operation of the Cassini spacecraft is centered at the JPL in Pasadena, California. The Huygens Titan Probe was operated from the Huygens Probe Operations Centre in Darmstadt, Germany. The Cassini mission planning, real-time operations, science planning/sequence integration, navigation, and spacecraft operations teams, as well as the program management, are co-located at JPL. The science teams are led using a distributed operations structure to allow scientists to operate their instruments from their home institutions, which are spread across different states and even different countries. Cassini instruments that serve multiple investigations are called facility instruments. Facility instruments were provided by JPL, NASA Goddard Space Flight Center or by ASI. A JPL team called the instrument operations (IO) team operates the facility instruments, except for INMS. Instruments that serve individual investigations are provided and operated by a Principal Investigator (the INMS is operated like a Principal Investigator instrument). For teams not resident at JPL, an Investigation Scientist or dedicated member of the Instrument Operations team assists in timely production and review of sequence products. A list of the remote ops team sites:

- JPL: RSS, RADAR, Science Planning, Mission Planning, Uplink Ops, S/C ops, Navigation, IO, Management
- Boulder, CO: ISS, UVIS
- Tuscon, AZ: VIMS
- San Antonio, TX: CAPS
- Iowa City, IA: RPWS
- Ann Arbor, MI: INMS
- Maryland: CIRS, MIMI
- London, UK: MAG
- Germany: CDA, Huygens

Distributed operations places observing decisions, including generation of instrument internal subsequences, in the hands of the science teams. The implementation of distributed operations for the Cassini mission is achieved through computers, computer-resident software and communication lines provided by JPL to the remote sites, as well as science participation in the uplink (mission planning, sequence development) and downlink (Principal Investigator instrument health monitoring) processes. Cassini uses virtual teams for mission planning and sequence development. These teams bring together people for the development of a given product. The product generation for a particular sequence block (covering 4 weeks of activity, typically) takes ~20 weeks to generate, requiring multiple virtual teams to be working at any one given time. Also, science data accounting was labor intensive due to the memory architecture (which was typical of the architectures of the time for spacecraft).

Instrument development for operability plays a key role in cost of science operations. Some areas that Cassini instruments could have improved for better ease of operations: 1) more complete development of instrument flight rules before launch so that the operations team can more realistically plan activities beforehand, 2) better instrument accommodation to minimize impacts on the operations of the other instruments, e.g., radiator placement. Areas that Cassini instruments did provide for operability include: 1) data compression internal to instrument for a cleaner interface between the spacecraft team and the instrument team, 2) some of the instruments have internal sequencing memory for storing instrument commands for the upcoming sequence to further decouple themselves from spacecraft resource management, and 3) for real-time non-interactive instrument commands, some of the instrument can also bypass the sequencing process by using the ASP tool.

Ground System Interfaces

Cassini is the earliest of the 4 missions studied in this report, with Phase B starting in 1989, with capabilities and technologies of that time. Many of the capabilities now used in more recent missions such as MRO, MER, MESSENGER and New Horizons were not available when Cassini was being designed and implemented. Although some features, such as web-based tools have been incorporated, the Cassini design largely reflects decade-old systems and architectures.

Many of the ground software planning tools were immature or unavailable at the start of the science planning for the prime mission. This resulted in homegrown tool development at the instrument sites and across the ops teams. System engineering of these types of ground software tools were lacking without sufficient resources need to be applied to Phase C development, so that the tools are not integrated and require the responsible teams to run them. Streamlining the tools, teams, and processes then becomes difficult. This led to accommodating remote operations with some attempt to standardize the interfaces but still enabling the science teams to work with their own tools. Allowing the science teams to use their own tools turned out to create additional problems; during science planning the teams using different tools produced differing results for the same spacecraft activities these conflicts then required additional analysis and reconciliation by the spacecraft and planning teams.

All of these issues (Spacecraft operability, ground system, and science operations) are a key part of the reasons why the uplink process takes 22 weeks prime mission (26 weeks in extended mission when new mission plans are in place) to develop a 4-week sequence of activities. This process requires that at any one time there are at least 5 sequence blocks being developed at various stages of definition each with a dedicated team. Improvements in spacecraft operability, more updated and integrated ground system planning and analysis tools, and a more cost-restrained science team

will significantly reduce a future outer planets mission as compared to Cassini.

K.1.3.3 New Horizons Mission Summary and Primary Cost Drivers

K.1.3.3.1 Mission Summary

New Horizons will be the first mission to perform a close-up flyby of Pluto, its moons including Charon, and potentially a Kuiper belt object. Launched on January 19, 2006, the New Horizons spacecraft will have a 9.5-year journey before reaching its closest approach (~12,500 km) to Pluto on July 14, 2015. During the 9.5-year cruise to Pluto, a single gravity assist was performed as the spacecraft encountered its closest approach of Jupiter (~32 Jupiter radii) on February 28 2007, a little more than one year after launch. This is the only gravity assist required during the entire mission. Leading up to the Jupiter Gravity Assist (JGA) there were only three trajectory correction maneuvers (TCM) required to target the Jupiter flyby aimpoint. There is not another TCM expected until the final months leading up to the Pluto/Charon encounter. Nine months out of the year the spacecraft is in hibernation mode with only a single beacon contact per week and a single telemetry contact per month. A single gravity assist coupled with a low number of TCMs and relatively large flyby distances has helped simplify the overall operation and reduce mission risk. The ability to place the spacecraft in hibernation mode greatly reduces operational costs.

Aspects of the mission architecture that most affected mission operations costs include:

- Simple mission design profile minimizes number of gravity assists and TCMs, reducing operational complexity and risk
- Spacecraft can be placed into hibernation mode during long cruise periods minimizing operational staffing levels and DSN costs
- Single opportunity for Pluto encounter leaves zero tolerance for errors. Requires extensive planning and testing effort to ensure encounter sequence accuracy and robustness.

K.1.3.3.2 Primary Cost Drivers

Management and Project Organization

The New Horizons team is comprised of three organizations (APL, SWRI, and Kinetix) with a total of eight teams during the post-launch phase. A majority of the teams are co-located at APL in Laurel, MD, except for the payload and SOC teams which are located at SWRI in Boulder, CO and the navigation team which is located in Arizona. The New Horizons mission is managed by a single Principal Investigator (PI), Alan Stern. Having only one PI has facilitated the management of the science operation by providing clear guidance to the science teams on science observation priorities and science related operational issues. The high level of co-location has facilitated the operation by making it easier to access key staff when needed, and minimizing travel requirements needed to support reviews and meetings.

- Single PI lead mission. Facilitates management of the science operation, provides clear guidance on science priorities and conflict resolution.
- Majority of teams are collocated. Allows quick access to key staff when needed. Provides strong, cohesive relationships amongst team members. Minimizes travel requirements.

Flight System Interfaces

The New Horizons spacecraft is of a small, agile design with both 3-axis and spin stabilized control modes. 3-axis control is required for science operations and the spin-stabilized mode is used during the cruise and hibernation phases. The spacecraft employs redundancy for most components, including G&C sensors and actuators, major electronics, flight processors and data recorders. There are no reaction wheels and all spacecraft trajectory and attitude control is done via thrusters. The power system utilizes a radioisotope thermoelectric generator (RTG). The thermal system is based on a “thermos bottle” design to maintain safe operating temperatures with minimal operations intervention. The science payload consists of seven instruments, including Ralph (visible and infrared imager), Alice (UV spectrometer), PEPSSI (energetic particle spectrometer), SDC (dust counter), LORRI (long-range imager), SWAP (solar winds and plasma spectrometer) and REX (radio science experiment). The spacecraft uses a fixed high-gain and medium-gain antenna for communications with Earth via the DSN.

- Small, agile design with no moving parts reduces operational complexity.
- A wide range of system redundancy coupled with extensive, well-designed fault protection simplifies operations and reduces mission risk.
- Power system RTG and thermos bottle design simplifies operations.
- Passive-spin stabilized design allows operation of the spacecraft in open-loop control mode. Allows for long-term hibernation mode and reduces risks for many operational activities.
- Limited resources need to be tightly managed to execute Pluto encounter (i.e., power margin, thruster counts, memory space, and bandwidth). Significantly complicates encounter sequence development and execution.

Mission Operations

Mission operations for New Horizons is managed by the APL mission operations (MOPS) team in Laurel, MD. MOPS is responsible for all spacecraft realtime command, control and assessment functions. MOPS interfaces with the DSN to schedule and coordinate realtime contacts with the spacecraft. MOPS is also responsible for supporting the mission planning process and translating activities from the master schedule into spacecraft command sequences. As part of this process MOPS is responsible for building and maintaining all models, constraints and documentation associated with the operation. MOPS also performs all software and hardware simulation activities required to validate command sequences. MOPS interfaces with the spacecraft and instrument engineering teams, the navigation team and program management to coordinate long term planning and day to day operations. The mission operations staff was at its highest levels through launch, commissioning and the Jupiter flyby campaign. During the nine month hibernation period each year, MOPS staffing is at a minimum level.

Science Operations

The SWRI team in Boulder, CO lead by PI Alan Stern manages Science operations for New Horizons. The SWRI team defines science observation details and priorities, provides instrument commanding details, and manages instrument engineering issues. For the Pluto/Charon encounter the science campaign will span one year centered ±6 months around closest approach. Since there is only one opportunity to execute the encounter, extensive measures are taken to ensure sequence accuracy and robustness. Due to the long duration of the cruise phase, Pluto encounter planning and testing is being done early while the most knowledgeable staff is still available. There is a plan to perform at least two Pluto encounter rehearsals prior to the actual encounter in 2015. Following the encounter it is estimated that it will take six months to play back all of the science data. There is also an extended mission following the retrieval of the Pluto/Charon science data. During this extended mission one or more Kuiper belt objects may be targeted for flyby or distant observation.

Ground System Interfaces

The New Horizons ground system is based on extensive heritage from the NEAR, CONTOUR and MESSENGER programs. The core realtime command and telemetry system is the EPOCH 2000 system provided by Integral Systems Inc. (ISI). The APL software group also develops and maintains software to provide functionality not provided by the core EPOCH system. The New Horizons planning and scheduling system is based on the JPL suite of planning tools, SEQADAPT and SEQGEN. In addition, MOPS uses a contractor developed software simulator tool (STATESIM) to process and validate command sequences. Assessment functions are supported by APL developed software tools, engineering dump (telemetry decom) and Plotter (data plotting). The MOPS team also utilizes a high-fidelity hardware in the loop simulator (NHOPS) for testing. APL provides a secure network allowing team members to remotely use the ground system. The Science Operations Center (SOC) is located at SWRI and has a direct interface to the APL MOC.

K.1.3.4 MESSENGER Mission Summary and Primary Cost Drivers

K.1.3.4.1 Mission Summary

The MErcury, Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission is a Discovery Class mission that will become the first spacecraft to

orbit Mercury, the inner-most planet in our solar system. MESSENGER was launched on August 3, 2004 and will cruise through the solar system until March 2011, gradually altering its path about the Sun to more closely match that of Mercury until Mercury Orbit Insertion (MOI). Once in Mercury orbit, MESSENGER's prime science mission begins and will continue for one Earth year (two Mercury solar days). The primary science goal of the first Mercury solar day is to obtain global mapping measurements from various instruments, while the second Mercury day will focus on targeted science investigations.

Aspects of the mission architecture that most affected mission operations costs include:

- Multiple-gravity-assist trajectory with one Earth, two Venus, and three Mercury fly-bys; science activities are conducted during each of these flybys except for Venus-1.
- Five deterministic deep space maneuvers and an orbit insertion burn are required.
- Once in Mercury orbit, a correction maneuver will be required approximately every 88 days to maintain the spacecraft's orbital position. The timing of these maneuvers is critical and constrained due to the need to orient the sunshade to protect the main body of the spacecraft from direct sunlight.
- Spacecraft momentum is controlled passively so that propulsive momentum dumps can be minimized and are not routinely planned.

K.1.3.4.2 MESSENGER Primary Cost Drivers

Management and Project Organization

The Johns Hopkins University Applied Physics Laboratory (JHU/APL or APL) designed, built, and manages MESSENGER. APL continues to manage spacecraft operations and the science team under the guidance of the Principle Investigator (PI), Sean Solomon of the Carnegie Institute of Washington. KinetX, Inc. is part of the project team, and provides the mission navigation services and products. Applied Coherent Technology Corporation (ACT) has been contracted for help with SOC implementation and development of the Planetary Data System (PDS) archive products. The Deep Space Network (DSN) provides the required ground antennas and communication network interfaces. MESSENGER averages three 8-hour tracks per week during cruise, with additional time for critical activities, and expects to have one 8-hour track per day during orbital operations for two years. The MESSENGER program supports the typical set of NASA mission reviews, including formal external reviews for critical Phase E events, such as flybys and orbit insertion. Development of the orbital concept of operations (ConOps) and detailed planning were deliberately deferred until Phase E, including maturation of a key science optimization, planning and sequencing utility called SciBox. The spacecraft and ground system did have full functionality to execute the mission at launch, although two flight software loads were planned during the Cruise period to correct any code deficiencies or add desired enhancements.

Associated cost drivers summary:

- Single PI lead mission. Facilitates management of the science operation, provides clear guidance on science priorities and conflict resolution.
- Majority of teams are collocated. Allows quick access to key staff when needed. Provides strong, cohesive relationships amongst team members. Minimizes travel requirements.
- SOC co-located at APL along with Mission Operations.
- Development of the orbital concept of operations (ConOps) and detailed planning were deliberately deferred until Phase E, including maturation of a key science optimization, planning and sequencing utility called SciBox.

Flight System Architecture

MESSENGER is a single spacecraft mission whose critical components are block redundant, non-critical components are functionally redundant, and has nearly-full box-level cross-strapping. The spacecraft has three basic modes: Operational, Safe Hold, and Earth Acquisition. Additionally, the Autonomy subsystem has its own set of modes (test, cruise, MOI, and orbit) to control which protective measures are active for a given point in the mission. The Autonomy subsystem provides fault protection for the spacecraft through the implementation of a rule-based engine and response macros. The Guidance and Control (G&C) subsystem has internal

modes that match those of the spacecraft, in addition to containing further subdivisions such as the solar arrays having three unique control modes. Both the Autonomy and G&C subsystems are managed by manipulating on-board parameters and user-controlled options.

The MESSENGER flight system is three-axis controlled through the use of reaction wheels, two co-aligned star trackers, Sun sensors, IMUs, and decoupled 4.4 N and 22 N hydrazine thrusters. It also contains a 660 N engine and bi-propellant subsystem.

The Power and Thermal subsystems were specially designed for the inner solar system (<0.7 AU), including an 8′ × 6′ ceramic-fabric sunshade and gallium arsenide solar panels that are 2/3 OSR materials. The power generated by the solar arrays is inversely related to the Sun distance. Since the spacecraft was specifically designed for operations near or at Mercury, periods outside of 0.7 AU required special handling such as “flip-flopping” the spacecraft at farther Sun distances to allow direct sunlight to heat the body, conserving power. Throughout the mission, power/thermal management is required for all eclipse periods to maintain battery discharge current constraints, and during all orbital “hot-planet” periherm periods when thermal radiation from the planet can damage spacecraft components.

MESSENGER has two main processors with a total of four code images (one is the active RAM executable) that house both the Command and Data Handling (C&DH) and G&C flight software. The autonomy software resides in two fault protection processors that have a total of four code images. The payload consists of nine instruments with seven individual processors and flight code (two images per processor) with common prime and redundant Data Processing Units (DPUs). The C&DH subsystem contains a total of 1024 macros for command sequence execution, ephemeris loading, and user-defined on-board blocks (OBBs); autonomy contains its own separate macro space.

The Communication subsystem (Comm) uses X-band to provide a maximum data rate of 104 kbps and an emergency rate of 10 bps through a phased array antenna high-rate antenna, a fanbeam antenna, and low-gain hemi antennas to the DSN. The Comm subsystem also supports ranging and DDOR activities with the DSN, as well as Radio Science (RS) measurements at Mercury. Data return can be maximized by optimizing the downlink rate through a series of “stepping” functions tailored for each DSN ground station and sequenced based on the DSN allocation schedule.

Associated cost drivers summary:

- There are multiple spacecraft modes, with several subsystem (G&C and Autonomy) having their own internal sub-modes that control the overall configuration and behavior.
- MESSENGER has over 2500 user-defined and maintained parameters. For any given activity, approximately 100–150 of these must be modified. Maintaining knowledge of, and the precise values of each of these places a heavy burden on the operations team.
- There are some impingement issues with the thrusters, as they can interact with the solar arrays at certain panel positions, causing the team to develop an array management scheme dependent on the type of burn and the solar distance at which it is being performed.
- MESSENGER has multiple articulating mechanisms, including two single-axis gimbaled solar arrays, the MDIS pivot, and electronically steered phased array antennas.
- Extra care is required to control where the spacecraft center of mass (Cm) is relative to the body, and necessitates performing a propellant centering burn after large thruster firings to relocate the fuel thus shifting the Cm. Alternate techniques are being implemented as well, including attitude alternations during non-contact periods to help minimize the total propellant used during cruise.
- Since the spacecraft was specifically designed for operations near or at Mercury, periods outside of 0.7 AU required special handling such as “flip-flopping” the spacecraft at farther Sun distances to allow direct sunlight to heat the body, conserving power.
- Throughout the mission, power/thermal management is required for all eclipse periods to maintain battery discharge current

constraints, and during all orbital "hot-planet" periherm periods when thermal radiation from the planet can damage spacecraft components.

- The payload consists of nine instruments with seven individual processors and flight code (two images per processor) with common prime and redundant Data Processing Units (DPUs).
- Science and housekeeping data is stored on a 1 GB standard Solid State Recorder (SSR) that utilizes an on-board file system and the CCSDS File Delivery Protocol (CFDP) for data playback and management.

Mission Operations

Mission operations for MESSENGER is managed by the APL mission operations (MOPS) team in Laurel, MD. MOPS is responsible for all spacecraft realtime command, control and assessment functions. MOPS interfaces with the DSN to schedule and coordinate realtime contacts with the spacecraft. MOPS is also responsible for supporting the mission planning process and translating activities from the master schedule into spacecraft command sequences. As part of this process MOPS is responsible for building and maintaining all models, constraints and documentation associated with the operation. MOPS also performs all software and hardware simulation activities required to validate command sequences. MOPS interfaces with the spacecraft and instrument engineering teams, the navigation team and program management to coordinate long term planning and day-to-day operations.

Associated cost drivers summary:

- Team has extensive operations heritage (planning, sequencing and testing processes) from NEAR and CONTOUR missions. Strong familiarity with APL built spacecraft and ground systems.
- All new and critical activities and products are tested on a hardware-in-the-loop simulator, with a faster-than-realtime software simulator used for all routine command sequences.
- Many team members support multiple functional areas, reducing staff size.

Science Operations

The payload consists of a wide-angle and narrow-angle imager, an atmospheric and surface composition spectrometer, a magnetometer, a gamma-ray and neutron spectrometer, an energetic particle and plasma spectrometer, an X-ray spectrometer, a laser altimeter, and RS. A primarily co-located science team manages the instruments with science goals and observations coordinated through a single PI, discipline groups, a weekly coordination meeting, the Payload Operations Manager (POM), and a unified Science Operations Center (SOC) located at APL. A typical cruise sequence period is two weeks long and requires six planning weeks, with one week long sequences planned for orbit. All science operations are coupled to the spacecraft sequencing, and must balance shared power, pointing, and data resources. A typical two-week cruise period produces ~2 Gb of data, a core flyby period of five hours produces ~7 Gb of data, and the total mission is expected to generate between 20 and 90 GB depending on total duration and DSN coverage.

Associated cost drivers summary:

- Science teams work cooperatively and are managed by a single PI to prioritize science observations.
- For large coordinated events, such as flybys or MOI, a Critical Event Planner (CEP) oversees a phased production of the integrated command sequence.
- A typical cruise sequence period is two weeks long and requires six planning weeks, with one week long sequences planned for orbit.
- All science operations are coupled to the spacecraft sequencing, and must balance shared power, pointing, and data resources.

Ground System

The MESSENGER ground system is based on extensive heritage from the NEAR and CONTOUR programs. The core realtime command and telemetry system is the EPOCH 2000 system provided by Integral Systems Inc. (ISI). The APL software group also develops and maintains software to provide functionality not provided by the core EPOCH system. The MESSENGER planning and scheduling system is based on the JPL suite of planning tools, SEQADAPT and SEQGEN. In addition, MOPS uses a contractor developed software simulator tool (STATESIM) to proc-

ess and validate command sequences. The APL developed software tools engineering dump (telemetry decom) and Plotter (data plotting) provide semi-autonomous (requires human oversight) assessment functions. The MOPS team also utilizes a high fidelity hardware-in-the-loop simulator for testing. APL provides a secure network allowing team members to remotely use the ground system.

A combination of manual and software verification tools are used to verify all of the command inputs, including those from the science teams. All new and critical activities and products are tested on the hardware-in-the-loop simulator, with the faster-than-realtime software simulator used for all routine command sequences. For large coordinated events, such as flybys or MOI, a Critical Event Planner (CEP) oversees a phased production of the integrated command sequence. Two phases (A and B) represent full builds and testing of this sequence with Phase-A culminating with a successful hardware simulation, and Phase-B with execution on the spacecraft. Oversight of this crucial sequence transitions from the CEP to the MOPS Lead at the start of Phase-B. The final tool set for orbital science operations was deliberately deferred into Phase E and is currently under development. All spacecraft telemetry is archived at APL, and all science data is pushed over to the MESSENGER SOC located at APL for processing and PDS population.

Associated cost drivers summary:

- The MESSENGER ground system is a combination of COTS and GOTS products, such as the SeqAdapt and SeqGen AMOS tools and the EOPCH T&C system, wrapped with APL in-house generated glue-ware and utilities.
- Extensive ground system heritage from previous mission for both realtime operations and mission planning and sequencing. Reduces costs and risks associated with new development and teams needing to learn and test a new system.

K.1.3.5 Relative Cost Driver Comparisons

The study team numerically scored each of the four mission's complexity by evaluating those attributes that most affected operational complexity. The results for each mission are listed in **Table K.1-1**. As can be seen by "total weighted average score", the Cassini mission ranked the most complex overall. The Cassini mission ranks highest in complexity in every category. MESSENGER and MRO are nearly tied for second (well within the error bounds of the estimates) with New Horizons operations rated the least complex overall. The drivers for obtaining the relative scoring for each mission are included in each mission's costs drivers as described in the preceding report sections.

As each cost driver category can not be treated equally (i.e., thermal control operations are not as difficult in general as G&C). To help correct for this in computing the average scores, a weighting was applied as shown in **Table K.1-1**. Individual flight system interfaces were scored and the weighted scores shown in the roll up line. This line was then weighted relative to the other major categories

Table K.1-1. *Relative mission complexity.*

Level of Difficulty 4 = Highest; 1 = Lowest	Weighting Factor		MSGR		NH		Cassini		MRO
Mission Architecture	2		3.5		1		4		3
Mgmt and Org	2		1		2		4		3
Flight Sys Architecture (roll up)	4		2.8		2.0		3.3		2.0
System	1	**3**	3	**1**	1	**3**	3	**3**	3
G&C	1	**3**	3	**1**	1	**4**	4	**2**	2
Power	0.5	**2**	1	**3**	1.5	**3**	1.5	**1**	0.5
Prop	0.5	**4**	2	**1**	0.5	**2**	1	**1**	0.5
Thermal	0.25	**2**	0.5	**1**	0.25	**2**	0.5	**1**	0.25
C&DH/SSR	1	**2**	2	**3**	3	**4**	4	**2**	2
Comm	0.5	**3**	1.5	**2**	1	**2**	1	**3**	1.5
Payload	1	**3**	3	**3**	3	**4**	4	**2**	2
Science Operations	3		3		3		4		3
Ground System Interfaces	1		2		2		4		3
Total Average Score			**2.6**		**2.1**		**3.8**		**2.7**

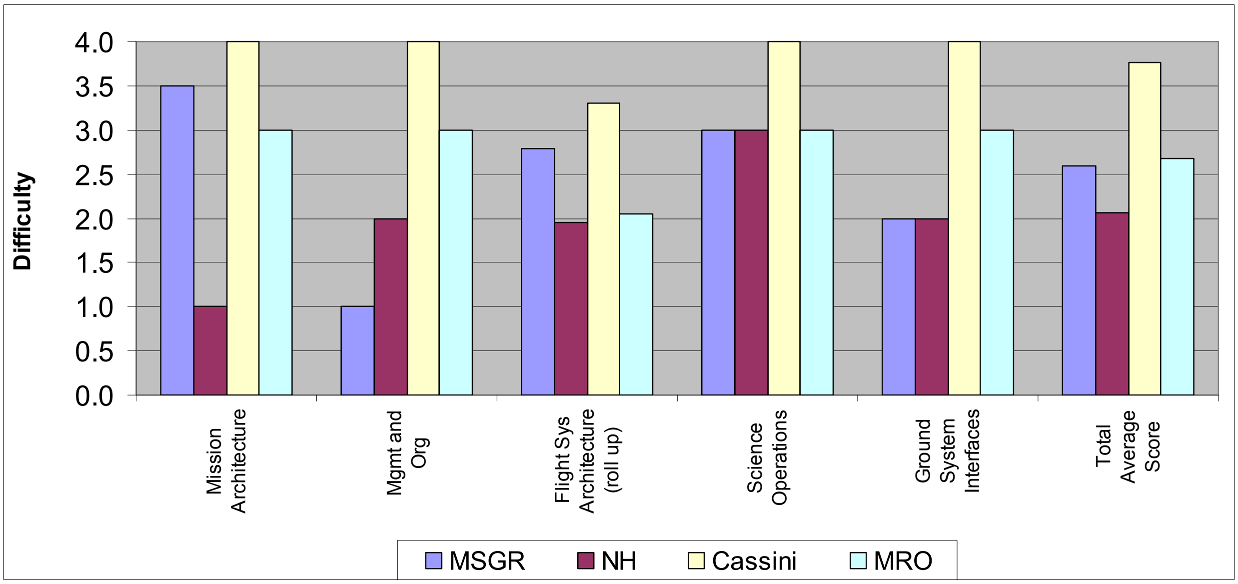

Figure K.1-2. *Relative mission complexity.*

and then averaged. The Flight System Interfaces were given a weight of 4, followed by a 3 for science operations, 2s for mission architecture and organization, and finally a 1 for ground system interfaces. While one can argue about the individual weights, the important point is the application of the weights tended to amplify the average score separations rather than alter the relative complexity order. These same scores are plotting in **Figure K.1-2**.

It should be noted that while this study focused on what made the missions complex and hence costly to operate, all missions studied included a number of ingenious operations features that enabled the operations or made them more efficient. The studies recommendations and conclusions (reference §K.1.5) are largely drawn from comparing what worked and what did not work for these for missions.

K.1.4 MO & GDS Staffing and Comparisons

The cost of Phase E operations were assessed in terms of total FTE at 3 points in each mission: 1) launch operations which typically represent a peak in operations staffing levels, 2) launch plus one year which typically represent cruise operations, and 3) prime science phases which are representative of the final mission staffing. It should be noted science operations costs data proved to be problematic to collect for each mission due to programmatic and contractual barriers in reporting costs to APL and JPL. This made is impossible to compare "apples to apples" for science operations staffing levels at this time.

The cost of Phase B and C/D preparations are reported and compared as a sum for each phase so that the relative cost for each mission to reach the same level of maturity could be compared. What follows are descriptions and data for each missions staffing levels in the four primary operations areas, including mission operations, ground data systems, navigation (post launch only), and engineering support.

Side-by-side comparisons of the four missions for pre and post launch staffing levels are shown in §K.1.3.4.

K.1.4.1 MRO Mission Operations and GDS Staffing

The MRO development started while the transition from the faster-better-cheaper philosophy to more of a traditional development had just begun. Mission success is number one priority. During the development phase many development activities sprung forth due to the new philosophy to achieve success in the mission as a top priority.

K.1.4.1.1 MRO Development Phase Staffing

In Phase A/B, MRO spent 99 work-months (WM) in the area of MOS development and six WM in the GDS development. In Phase C/D, MRO spent 580 WM in the area of MOS development and 372 WM in the area of GDS development.

Table K.1-2. *MRO Phase E, MO&GDS staffing.*

Categories	12/1/2005 (Cruise)	3/1/2006 (MOI)	7/1/2006 (Aerobraking)	7/1/2007 (PSP)
Management Staff	2.0	2.0	2.0	2.0
MOS/GDS System Eng.	6.0	7.1	7.2	4.4
MOS Development & Ops				
Flight Engineering Team (at LMSS)	24.4	26.6	26.6	16.0
Navigation Team	8.9	10.2	10.9	6.3
Mission Planning and Sequencing Team	3.0	3.0	4.3	3.0
Payload Operations Support Team	3.0	3.0	3.0	3.0
End-to-end Data Accountability Team	3.0	3.0	3.0	3.0
Others	8.0	8.0	8.0	5.0
GDS Development & Ops	3.1	4.0	2.8	2.5
Multi-mission Development & Ops	10.3	9.1	6.4	10.4
Total Staff Months	**71.7**	**76.0**	**74.2**	**55.6**

MOS development is defined to include mission management, mission operations system engineering, flight team development, flight operations process and interface development, science operations process and interface development, flight system scenario testing, training, and flight operations readiness tests. The GDS development is defined to include project unique software development, multi-mission software adaptation, integration and test, and hardware procurements.

K.1.4.1.2 MRO Phase E Staffing

Table K.1-2 shows the FTE associated with a few unique project milestones during MRO's operations phase.

The Flight Engineering Team number in the above table represents the total staffing at LMSS. This number includes LMSS management and administrative personnel, system coordinator, subsystem engineers, orbiter testbed operators, and real time operators. JPL provides supports for this team, including in the areas of system coordinators, ACS engineers and realtime operators. The number labeled with "others" represents the additional supports to the FET as described above in addition to the phase leads support. Phase lead is the lead engineer for a MRO phase as the MRO goes through launch, cruise, MOI, aerobraking, and primary science and relay phases. A comparison of MRO staffing levels to other missions for similar functions is included in §K.1.3.4.

K.1.4.2 Cassini Mission Operations and GDS Staffing

By any measure Cassini is a large and complex mission, and also predates all of the other missions studied in this report by many years. At the time it was on the leading edge of new operating and development paradigms, and using the then new technologies such as shared file systems like AFS, and the WWW. As such, the level of effort consumed during development was very significant. This large effort was fueled by several factors that are described earlier in §K.1.3.2.2.

K.1.4.2.1 Cassini Development Phase Staffing

The labor shown in **Table K.1-3** is broken into development phase (B and C/D) staffing. The development phase shows the total Ground system labor during development phases. The Phase E staffing presents 3 representative snapshots of the staffing to support cross mission comparison. This is done to minimize the potentially overwhelming impact of mission duration and provide a duration independent means to compare Cassini operations staffing to other missions. The development staffing for Cassini breaks out as follows:

This MOS development staffing includes the following mission operations and ground system related activities:

a) MOS Mgt and MOS Engineering.
b) Distributed operations interface engineering
c) Operations planning, engineering, training, and execution
d) Software development and testing in support of operations. This includes the small amount adaptation to the existing

Table K.1-3. *Cassini development phase staffing.*

	Phase B	Phase C/D	Total
MOS Development	72	4651	4723
System I&T and ATLO	48	1789	1837
Total Staff Months			**6560**

ground system software. This also includes new development in support of entirely new flight software, new planning and sequencing tools, new distributed file system and data distribution system, and distributed science operations centers.

MOS development does not include most of the science processing and instrument accommodation related development, which is book kept separately as part of the science costs.

The System Integration and Test development efforts include system I&T and ATLO related staff. This includes all of the spacecraft and ground system support utilized in the course of planning and performing ATLO.

K.1.4.2.2 Cassini Phase E Staffing

Cassini Phase E efforts included a significant amount of post launch development to accommodate the evolving planning tools needed to support the tour activities and to address the improved understanding of the spacecraft and better ways of operating the mission that came with experience.

Table K.1-4 presents the average monthly staffing FTEs at three points in the mission, shortly after launch, one year into the cruise, and during primary science operations.

The labor categories above include the following efforts:

- *Project Management:* Project management and related support staff.
- *Engineering Support:* This includes all of the spacecraft subsystem engineers and planning engineers required to fly the mission. In addition this would include the engineers involved in some of the tool development that didn't fall under the GDS tool development umbrella.

Table K.1-4. *Cassini Phase E staffing at launch, cruise and primary science.*

	Launch + 2 months	Launch + 12 months	Primary Science Ops
Project Management	13	13	9
Engineering Support	100	75	49
Mission Operations	42	28	15
Ground Systems	23	17	13
Navigation	22	18	30
Subtotal	**200**	**151**	**116**
SOC + Science Ops + Science Support	55	55	60

- *Mission Operations:* Includes the flight control team, the sequence team, data management team, DSN schedulers, science planners, and other people directly supporting mission operations but not tied to the spacecraft engineering team or ground system engineering team.
- *Ground Systems:* Primarily this is the set of people involved in maintaining the infrastructure for all project members, both hardware and software, including the communications infrastructure and the distributed science operations interfaces.
- *Navigation:* This includes the navigation operations and tool development performed during cruise to prepare for the tour. Once in the tour phase this staffing is used primarily to accommodate the constant maneuvering required (at least twice monthly maneuvers) to safely make all of the planned flybys and science observations. A factor that impacts navigation labor is the use of uncoupled thrusters on the spacecraft that complicate Orbit Determination and Trajectory analysis and requires additional labor to accommodate. Navigation also includes the mission design and planning work used in support of the flyby selection and design.

K.1.4.3 New Horizons and MESSENGER Mission Operations and GDS Staffing

MESSENGER and New Horizons missions followed the same basic approach to staffing their respective operations as both are operated from the same MOC at APL. **Figure K.1-3** shows the integrated total staff months for Phases B and CD separately for the two missions. Below is a description of what work is performed in each of the work categories represented.

K.1.4.3.1 New Horizons and MESSENGER Phase-B Staffing

Mission Operations Team

During this phase, a majority of the mission operations work is the responsibility of the Mission Operations Manager (MOM). Primary responsibilities of the MOM during this time period include:

- Refine Mission Operations Plan and derive operations related requirements
- Support development of the MOC-SOC and MOC-Ground Station ICDs

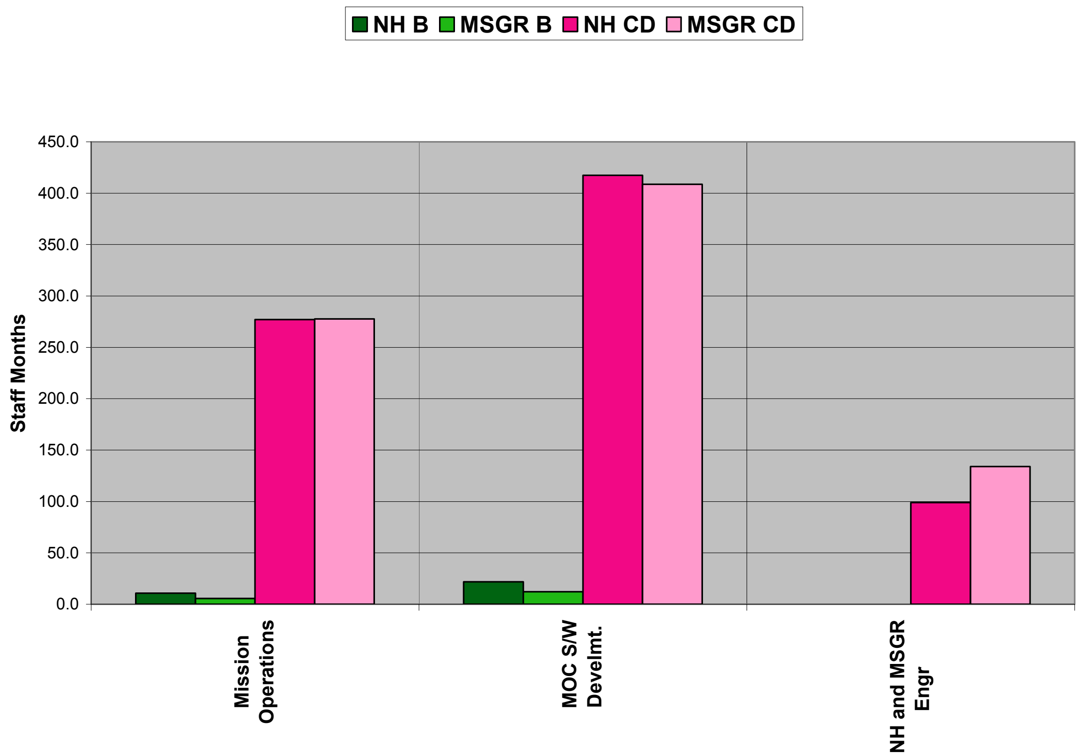

Figure K.1-3. New Horizons and MESSENGER Phase B&CD, MO&GDS staffing.

- Participate in spacecraft and ground system design trades
- Develop preliminary ground station plan and update MOC requirements
- Configure the Mission Operations Development Plan
- Develop Mission Operations PDR Presentation (request help as needed)
- Specify requirements for ground software tools

MOC Software Development Effort

During this phase, the ground software lead is overseeing ground system planning efforts. Tasks required during this phase include:

- Development of a Ground System Software Requirements document
- Development of a Ground System Concept of Operations document
- Leading the Software Requirements Review
- Provision of inputs to hardware procurement planning
- Documentation of the system level Software Development plan
- Identification of required ICDs, review hardware procurements, perform trade studies
- Development of integration test plans to support MOC and flight to MOC system testing
- Development of and presentation of the preliminary ground software design at the ground system PDR and mission level PDR

K.1.4.3.2 New Horizons and MESSENGER Phase-C/D Staffing Summary

Phase-C/D Mission Operations Effort

Primary responsibilities of the MOM and operations team during this time period include:

Detailed Design Phase

- Continue to refine MOPS plan, schedule, staffing and devise test plan
- Develop and document MOPS interfaces with SOC, Ground Station, Navigation & Mission Design
- Continue coordination efforts with ground system and ground station representatives

- Begin spacecraft and instrument knowledge capture to support User's Guide, command sequence and test plan development
- Review and support C&T database and display page development and maintenance
- Develop MOPS test plan and test verification matrix
- Develop MOPS CDR presentation and support Critical Design Review
- Continue to refine all program required MOPS documentation as needed
- Complete subsystem and instrument knowledge capture
- Complete MOPS inputs/reviews to C&T database
- Monitor and help test ground system deliveries
- Develop Mission Operations Review presentation and support review
- Complete documentation of MOPS interfaces
- Continue development of real-time procedures, command sequences, flight constraints and MOPS tools
- Complete MOPS test development, execution & requirements verification
- Train and certify flight controllers and mission analysts
- Support Launch & Early Operations and Flight Readiness reviews

Phase-C/D Ground Software Development Effort

- Ground software team finalizes detailed design of the ground system for each computer software component (CSC) based on earlier defined system requirements
- Software build review schedule is refined, identifying contents for each build
- Develop and present the ground software design at the ground system CDR and mission level CDR
- Software build reviews are held for each scheduled build delivery
- Implementation and unit testing is performed for each software build
- Source code is configured, unit tests are executed and reviewed for each build
- Formal acceptance testing is performed for each software build delivery
- Configuration management process initiated for requested changes
- Software executable deployment and release notes documentation
- Implementation and comprehensive testing is performed for each software build

K.1.4.3.3 New Horizons and MESSENGER Phase-E Staffing Summary

Figures K.1-4 and **K.1-5** show the relative FTEs for New Horizons and MESSENGER Phase E flight operations for each major category of work at launch, launch plus 1 year, and prime science operations. Both mission operations were on the same staffing scale and both started off with more than what they presently have or intend to have during prime science phases. It should also be noted that while the operations staffing is generally organized into two physically separate teams, some sharing of team members during peak periods of operations has begun. This has served to help level the number of total staff numbers. Below is a description of what tasks are included in each category plotted.

Engineering Support

Once control authority of the spacecraft transitions to the operations team at launch, varying levels of support is required from the spacecraft and subsystem engineers that designed and are the experts in their respective subsystems. Typical subsystem engineers include mission design, G&C, power, thermal, autonomy, C&DH/FSW, propulsion, and RF. These people are responsible for detailed training of the operations personnel and oversight of their subsystems, including assessment, anomaly resolution, and technical jurisdiction over all flight activities involving their subsystem or related components.

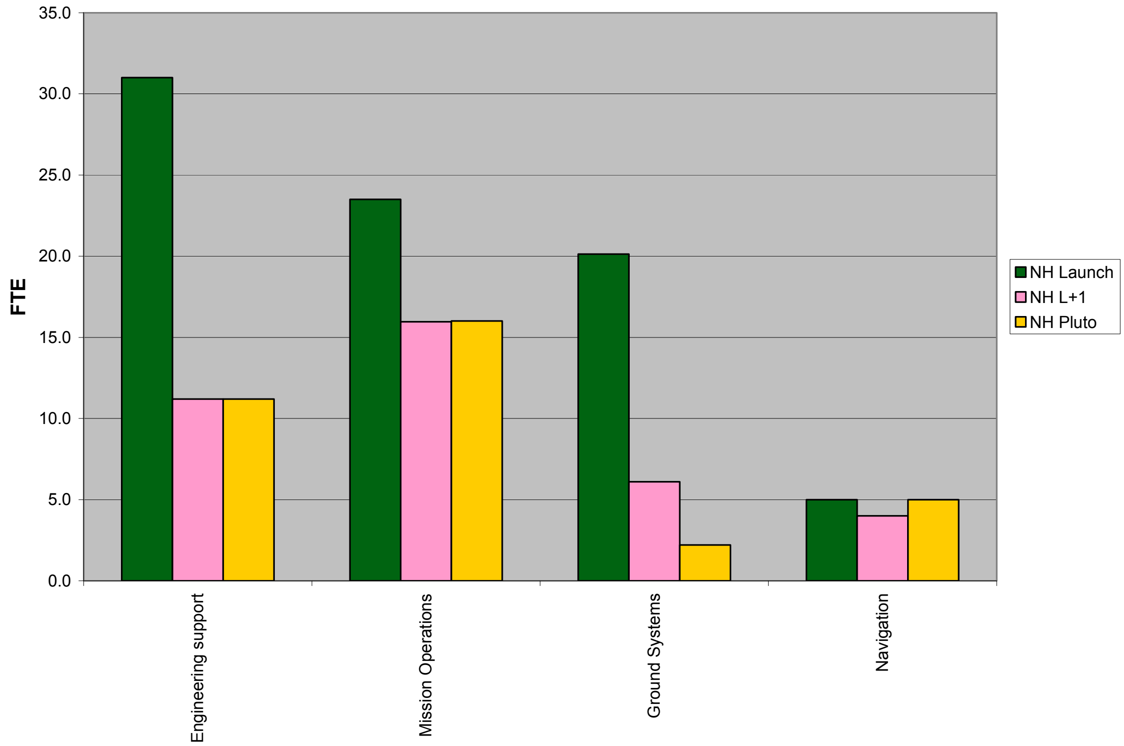

Figure K.1-4. New Horizons Phase E, MO&GDS staffing.

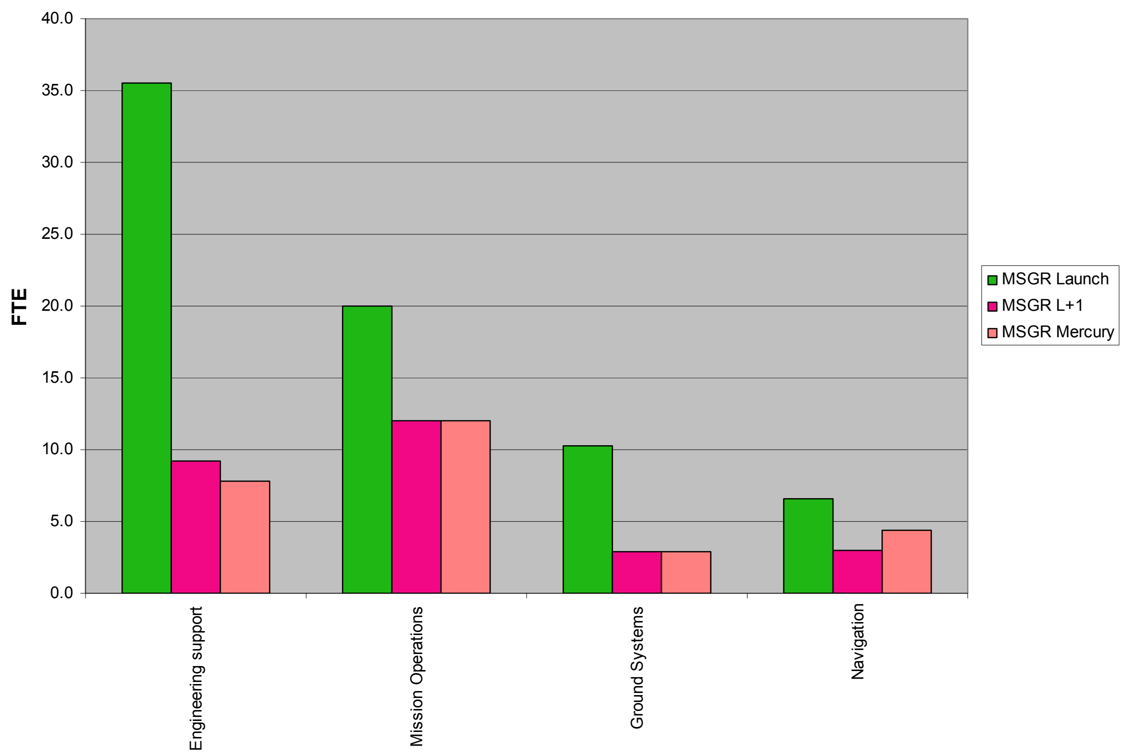

Figure K.1-5. MESSENGER Phase E, MO&GDS staffing.

Mission Operations

This work category captures those staff associated with the mission operations (MOPS) team. Typically this team is led by the Mission Operations Manager (MOM) and Deputy Mission Operations Manager (DMOM). There are mission analysts, or off-line staff responsible for the planning and day-to-day execution of specific spacecraft operations that act as the liaisons to the subsystem and instrument technical leads and other operational support elements, including navigation, DSN, and the ground system interfaces. Planning and execution of spacecraft events includes designing how an activity is to be performed, interacting as necessary with the appropriate technical leads, conducting reviews, testing, overseeing the eventual flight execution, and documenting the results as necessary. Mission analysts perform mission planning and sequencing tasks, DSN schedule coordination, spacecraft assessment, data distribution, science interfacing, and initial anomaly detection/resolution and recovery activities. This category further includes realtime flight controllers (FCs), or those staff that directly interface with the spacecraft through the telemetry and command system and with the DSN via network and voice interfaces, as well as the flight controller lead that is responsible for the management and scheduling of the FCs.

Ground System

The ground system work category for Phase E covers all of the staff associated with providing software fixes, and re-test as needed, to the baselined system in place at launch. These people ensure software fixes are documented and closed out in a controlled problem reporting system. Ground personnel provide the IT security plan as required by NASA IONET, and maintain monitoring applications and logs as required. This work element addresses all of the workstation system administration that includes setting up new equipment, maintaining the ground system to APL Space Department standards, managing user accounts, and establishing automated data back-ups. People within this element also provide communications system administration post-launch, including voice box and network setup and maintenance. Note, much of this support is shared across multiple missions, and the numbers shown are representative of only the mission specific services provided.

Navigation

The commercial organization KinetX, Inc. provides navigation support to the New Horizons mission. They are responsible for orbit determination, maneuver design, and trajectory reconstruction throughout the mission. They also provide launch support, pointing predicts, ephemeris files, and other navigational products to various project elements. The people under this work category work closely with mission design and G&C staff captured in other elements as described above.

K.1.4.4 Staffing Level Comparisons and Relative Complexity

K.1.4.4.1 Development Phase (Phases B and C/D) Staffing Comparison

Mission Operations and Ground Data System staffing levels were collected for each of the 4 mission studies. Pre-launch Phase B and CD staffing was summed over each project's phase boundaries. The resulting integrated staff-months are shown in **Table K.1-5**. For Phase B, MESSENGER expended the least amount of staff, and MRO the most. For Phase C/D, MESSENGER, MRO, and New Horizons were "in family" and Cassini was significantly greater, than the others missions and clearly "out of family" for the development phases.

Science operations costs were not compared due to the difficulty of passing the required data through the programmatic and contractual barriers and due to differences in reporting costs to APL and JPL. This made is impossible to compare "apples to apples" for his category at this time. As noted earlier, science operations by the science teams is not accounted here. To compare science operations costs,

Table K.1-5. *Integrated MO&GDS staff months for pre-launch preparations.*

	Phase B				Phase C/D			
	MSGR	NH	MRO	Cassini	MSGR	NH	MRO	Cassini
Mission Operations	5.5	10.8	99.0	60.0	277.7	277.1	580.0	2963.0
MOC S/W Devel.	12.2	21.8	6.0	12.0	408.8	417.4	372.0	1688.0
NH and MSGR Engr					134.1	98.9		
Staff Totals	**17.7**	**32.6**	**105.0**	**72.0**	**820.6**	**793.3**	**952.0**	**4651.0**

coordination at the PI or NASA HQ level would be required.

K.1.4.4.2 Mission Operation Post-Launch (Phase E) Staffing Comparison

Staffing levels for post launch operations were gathered at 3 key points in each mission, including launch, launch plus one year, and prime science operations. The staffing levels are plotted in **Figure K.1-6**. These include Mission Operations, Engineering, Ground Data Systems, and Navigation efforts combined. For the same reasons as discussed for the pre-launch staffing, these numbers do not include instrument support, science planning, or SOC development and operations.

Staffing during prime science operations for both MESSENGER and New Horizons are obviously at planned levels (yet to begin) whereas for MRO and Cassini they are actuals. Each mission except MRO had its greatest effort at launch. It was problematic to separate out the MRO engineering staff that supported ATLO versus that which supported the flight operation. Hence it is safe to assume MRO also had a larger team at launch than the rest of its mission phases yet it is not evident in **Figure K.1-6**. While Cassini's staffing levels are higher than the other 3 missions, they could be explained by the Cassini's overall mission complexity being a 3.8 vs. 2.6/2.7 for the next most complex missions MESSENGER and MRO (Reference **Table K.1-1**).

K.1.4.4.3 Mission Operation Post Launch (Phase E) Staffing vs. Complexity Comparison

To better compare and contrast each operation's complexity and associated staffing, an average staff was computed using the staffing levels shown in **Figure K.1-6**. That average staff was then plotted for each mission against its respective complexity as determined by the study team (see §K.1.4.4.1). The results are shown in **Figure K.1-7**.

This plot shows New Horizons, MRO, and MESSENGER are relatively near each other on the grid and Cassini is in its own in terms of both complexity and cost. A least squares fit of the 4 data points is shown as a blue line. The green line is an exponential fit of the same data. Both CAS and NH are above the linear fit while MSGR and MRO are both below it

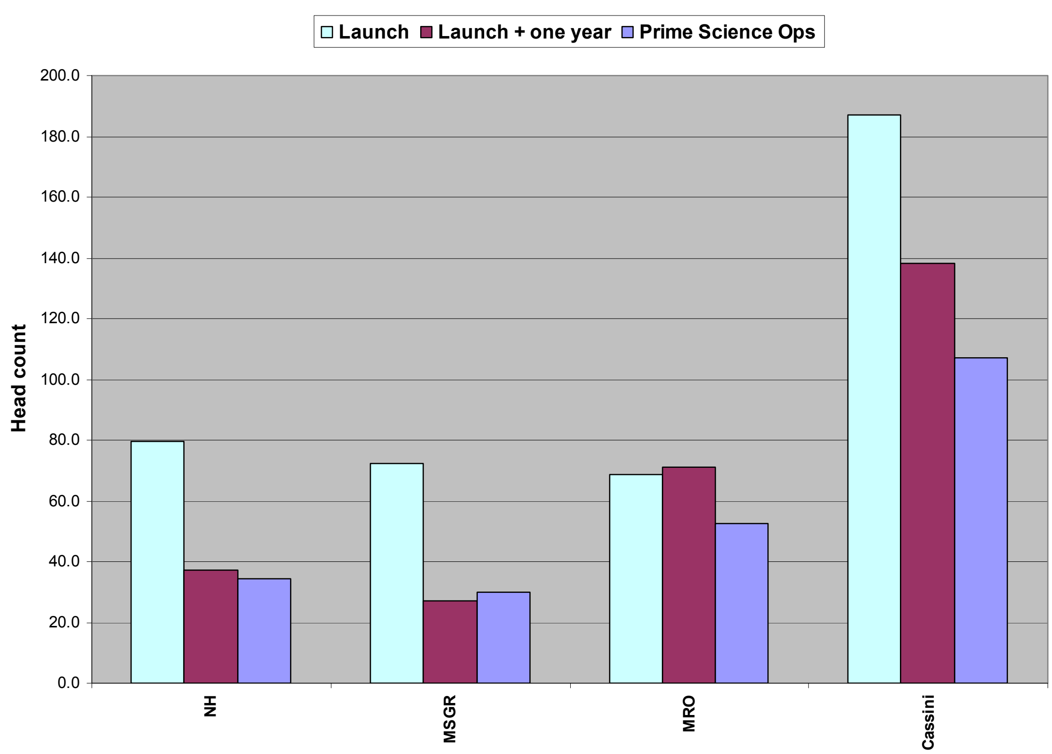

Figure K.1-6. Phase E operations staffing snapshots.

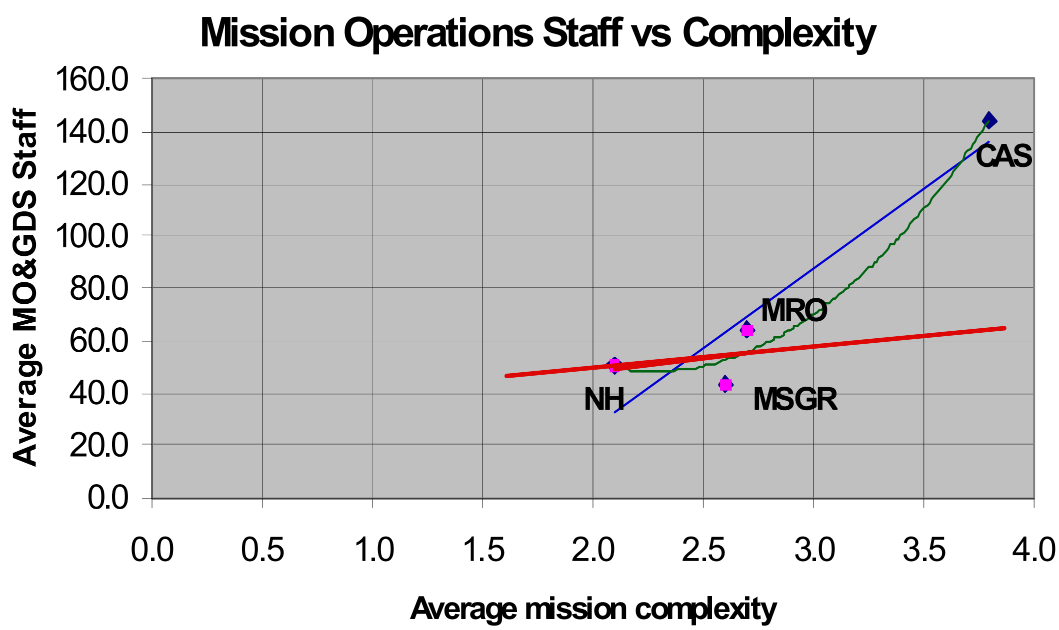

Figure K.1-7. *Phase E operations staff vs. mission complexity.*

indicating they may be the most efficient of the four operations. MESSENGER falls the furthest below, also falling below the exponential line indicating it *may* be the most efficient of the set. This would not be too surprising given it is the only Discovery mission in the set and hence cost capped. It was regularly stated by those that worked this mission when explaining the pressures experienced that MESSENGER is a "Flagship mission on a Discovery budget."

A least squares fit of the MRO, MESSENGER, and New Horizons points is shown with the red line. Extending this line at its slope to Cassini complexity levels does suggest Cassini and other missions of similar complexity would be expected to cost more, but less than current Cassini levels. Recommendations for reducing mission complexity and operations cost are summarized next in §K.1.5, *Recommendations for Reducing Flagship Phase E Costs*. These recommendations, if incorporated into the next OPF mission should result in significant cost savings for that overall mission operation.

K.1.5 Recommendations for Reducing Flagship Phase E Costs

This section captures the primary recommendations for reducing mission operating costs and total mission costs for future deep space missions based on the experiences of Cassini, MRO, MESSENGER, and New Horizons mission operations. While not all recommendations are within the control of the Project, they are included to inspire future mission implementation of lower cost mission operations. Also, some of the recommendations could also help to reduce development costs and cost risk as well.

Mission Design/Architecture

While there are a number of primary cost drivers stemming from mission architecture decisions (mission duration, complexity of the trajectory, complexity of the science mission), these are typically not negotiable unless science requirements can somehow be reduced or less demanding trajectories found. Hence the most practical way to save cost is to minimize the amount of activity during cruise, including use of hibernation-type modes and foregoing opportunistic science taken during gravity assist maneuvers and otherwise along the way to the primary destination. However, one should not discount the benefit of using these opportunities to train the operations team and test systems for eventual prime science operations.

Management and Organization

- Reduce the complexity of the contention resolution process by choosing a single PI. Streamline the arbitration process so that it

need not involve the majority of the mission planners. A strong "super PI" or Project Scientist could oversee this process.

- Co-locate mission planners or have representatives with decision making capability co-located to help reduce communications delays when iterating on plans.
- Investigate ways to streamline the ITAR/TAA processes for working with foreign instrument teams/individuals.
- Improve the process for communication within the project by providing a central document repository that is readily accessed by all project members, subject to ITAR restrictions

Flight Systems Interfaces

Evaluate operational complexity and incorporate ease-of-use features for each primary flight system with special emphasis on G&C and C&DH flight processor interfaces (as they are typically the most complex). While enhancing the operability of these interfaces may add to development and test scope, there are many features that can be incorporated that save considerably more money over the course of the mission than the upfront costs.

- As part of the next OPF mission design effort, formalize a joint operations and flight system design process for each proposed flight system to evaluate its design in terms of operability and quantify affect on total mission costs. Senior flight operations personnel could be temporarily assigned to augment the OPF operations team to assist in the assessment function. Note: This process was ad-hoc on past missions and subject to the availability and capability of the specific operations team involved in the early stages.
- Consider such features as: coupled thrusters, automated momentum management, scan or gimbaled platforms that can significantly reduce conflicts between instrument types (fields and particles vs. pointing) or between payload and communications system, deterministic slew paths, ephemeris based pointing.
- Ensure adequate power margins and consider predefined payload modes/configurations to simplify planning. Favor power over mass in use of PMDs, coupled thrusters, proper instrumentation.
- Incorporate a file system and pre-allocated (by ground rules) SSR space. Sufficient margins for command and SSR memory. Use automated file playback software and CFDP to minimize SSR management and to have automated retransmission for data dropouts. Consider CFDP for command uploads and potential use for telemetry.
- Strive for commonality in payload instrument telemetry and command interfaces.

Science Operations

- Incorporate a planning process that is efficient enough for Europa/Titan orbital operations, and modify as necessary for tour operations. Consider cost constraining planning tools (i.e., market based and priority based systems).
- Develop process that minimizes the number of planning iterations, bounds time allocated to planning each significant event, and incorporates the principle of "good enough."
- Develop an integrated planning and sequencing tool based on model-based engineering and state analysis that would be used throughout the project lifecycle.

Ground System Interfaces

- Incorporate information management systems (i.e., CIMS) for entire team's remote access to planning products, telemetry, command sequences, and action item tracking.
- Have a PI set priorities. Have ground system and planners implement those priorities and optimize supporting processes as needed.
- Incorporate resource modeling and flight constraints models in early in planning process for early identification of problems. Permit science planners access to models of similar fidelity as what MOC uses for end validation. Make accessible to distributed team.
- Incorporation of flight system faster than real-time software models for resource and constraints checking (i.e., SoftSim or Statesim).
- Adoption of unattended pass operations for non-command passes. Limit number of command passes. Rely on automated limits

and alarms checking versus manual, by FC or ACE.

- Unattended (automatic) radiation of non critical commands (i.e., SOHO or ACE)
- Streamlined/automated real-time process for late knowledge updates, including ephemeris and time shifts.
- Consider incorporating real-time automated assessment tools and post event trending tools (i.e., MRO).

Testing and Validation

- Adopt logical testing steps with software tools catching problems upstream (with faster than real-time software) of more sophisticated (real-time hardware) simulations.
- Incorporate software tools, scripts, to aid in H/W simulator setup and configuration control using planning system inputs for starting conditions. Use checkpoint and restart process for H/W simulations.
- Automate syncing of S/W sim (and H/W sim tools) with flight for proper configuration control. Perform periodic audits.
- Incorporate tools for post simulation data processing and distribution—reduce labor and time requirements.
- For geographically distributed team members, provide easy access to data for each reviewer. (i.e., MRO has web based results outside flight ops network)
- Have good validation of software simulators so they can be used in place of hardware simulators. Incorporate fidelity into software models match hardware simulations as closely (and quickly) as possible.
- Use real-time simulators by exception (only as needed), faster than real-time software for all nominal operations. Ensure adequate numbers and fidelity of real-time hardware simulators during each phase of the mission.

K.1.6 Acknowledgements

The study team would like to thank the following representatives of JPL's Cassini mission operations, most notably, Brian Paczkowski, for taking the time away from their ongoing operations duties to help describe Cassini operations processes:

- Laura Burke
- Dave Mohr
- Brian Paczkowski

In addition, the study team would like to acknowledge the participation of individuals from NASA ARC that participated in team discussions sharing with us relevant experience in automation approaches used on MER, Phoenix, and MSL.

- Mike McCurdy
- Jim Kurien
- Alonso Vera

Finally, the following members of JPL's OPF study teams also contributed to the working discussions and/or editing of the final report:

- Matt Bennett
- Robert Rasmussen
- Jan Ludwinski
- Thomas Magner

L. SUPPORT TO TSSM BY CASSINI EXTENDED EXTENDED MISSION (CASSINI SOLSTICE MISSION)

Our knowledge and understanding of the Saturn system have increased significantly as a result of data obtained by the Cassini-Huygens spacecraft during its successful prime mission and ongoing equinox mission. Prior to Cassini-Huygens, it was already known that Titan, Saturn's largest satellite, has a dense atmosphere of nitrogen with a few percent of methane. The Cassini mission has revealed a surface structure with mountains, rivers, lakes of hydrocarbons, dunes, impact craters and cryo-volcanic features. It is a complex system with interactions between the interior, the surface and the atmosphere where the geological processes that have shaped Titan's surface are similar to those existing on Earth-like planets with ices playing the role of silicates and methane and ethane that of water. Such a world cries out for a dedicated mission with an orbiter and *in situ* elements in order to study Titan as a global system and to investigate the evolution of organic chemistry leading to the formation of prebiotic molecules. Two major themes have emerged for a potential Cassini extended, extended mission named Cassini Solstice Mission (CSM): seasonal variations in the Saturn's system and preparation of a dedicated mission to Titan.

L.1 Observing Seasonal-Temporal Change

Titan's year is approximately 30 Earth years. Extending the Cassini mission allows Cassini to study seasonal processes. Cassini arrived in the Saturn system during the deep northern winter and our prime mission and equinox mission takes us only to spring (**Figure L.1-1**). With a potential seven year extended extended mission that would capture summer solstice, observations on the seasonal variations in Saturn's atmosphere, Titan's atmosphere, Titan's surface, and the long term variability of Enceladus' plume are possible. TSSM would arrive at a season complimentary to that of Cassini.

L.1.1 Titan Atmospheric Seasonal Variations

The formation and development of Titan's clouds is likely to depend on solar heating. During the four year nominal Cassini mission, the south polar cloud system vanished with smaller and sporadic cloud appearances, mid-latitude sporadic clouds were observed in the southern hemisphere and a giant cloud system

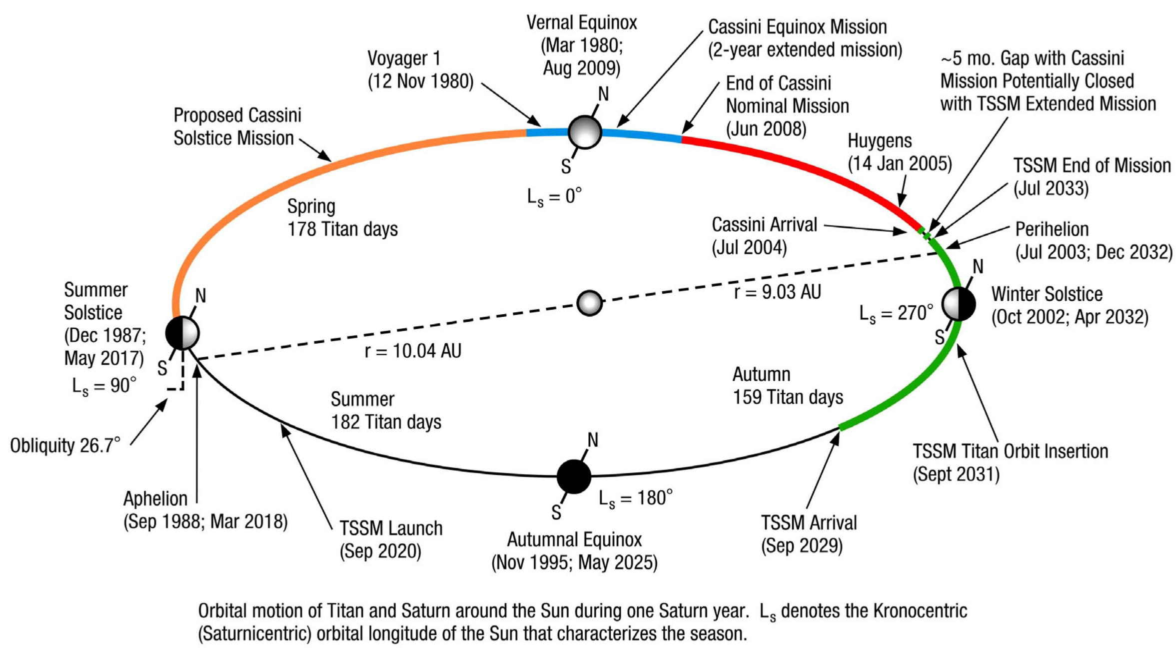

***Figure L.1-1.** Saturn's year, with Cassini's Prime, Equinox, and proposed seven year extended, extended missions. TSSM would arrive in a time period that is complementary to Voyager and Cassini missions.*

extending to 50° latitude has always been present on the north pole. The extension of the mission up to summer solstice would allow scientists to monitor the evolution of this system. For example, models (Rannou et al. 2006) predict that southern mid-latitude clouds should vanish.

The wind directions and velocities are also expected to change seasonally. The Cassini mission can monitor the wind directions and velocities in the upper atmosphere. The CSM should be able to observe the formation and breakup of the winter polar vortex.

As Titan goes from south to north of Saturn's solar-wind-warped magnetodisk from one solstice to the next, it will be important to observe Titan's plasma interaction and may allow the measurement of an induced magnetic field.

Lorenz et al. (2008d) recently proposed that the exchange of angular momentum between the atmosphere and the icy crust was responsible for the non-synchronous spin rate (Stiles et al. 2008). During the CSM, the predicted inversion in the wind directions should allow us to see a much larger deviation to the spin rate because the present effect is compensated by the long-term precession. If this observation is confirmed, it would tell us that the icy crust is decoupled from the interior and it would prove that an ocean is present at depth. If it is not confirmed, it does not rule out the presence of an ocean and a future mission to Titan will still be necessary in order to confirm or infirm the presence of such an ocean which has important implications in astrobiology.

L.1.2 Surface Seasonal Variations

The discovery of river beds carving the bright equatorial highlands suggest that precipitation must happen at some point during Titan's year as it is the case in many areas on Earth where there is a rainy season. Such precipitation has not yet been observed during the nominal mission and are expected during the CSM.

Lakes and seas have been discovered in the northern hemisphere by the radar instrument (Stofan et al. 2007). Only one major lake (Ontario Lacus) has been observed in the Southern hemisphere by optical instruments (Brown et al. 2008). A major question to be answered by the CSM is the fate of hydrocarbon lakes and seas. Is there a relation between the presence of the polar hood and the existence of numerous hydrocarbon lakes in the northern hemisphere (**Figure L.1-2**)? Do most of them dry out during the northern summer? Are they located in topographic lows where a subsurface hydrocarbon reservoir can be seen?

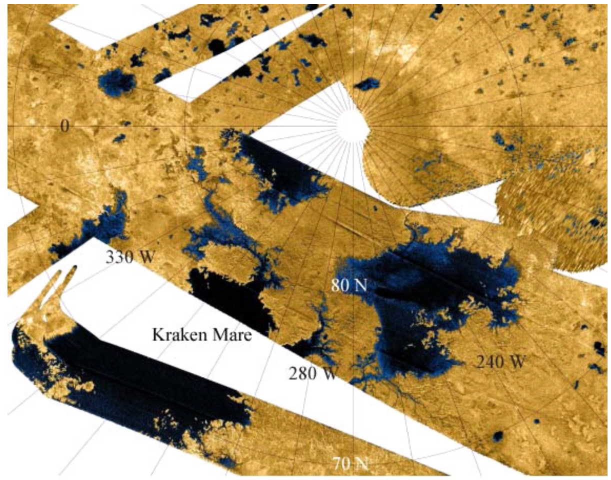

Figure L.1-2. *False color map of a mosaic of radar observations over the North Pole. One large sea is Kraken Mare where a lander could be delivered.*

L.1.3 Enceladus Plume Evolution

The discovery of plumes at Enceladus' south pole is a revolutionary discovery of the Cassini mission. Whether the activity of the plume is continuous or over various time periods is a question that can be addressed by the CSM. The variability of Enceladus' plumes will be investigated during that period of time.

L.1.4 Seasonal Variations in the Saturnian System

Several processes operating in the Saturnian system may show linkage between seasonal variations and solar heating or variations related to the solar cycle (**Figure L.1-3**). For example, spoke formation mechanisms will be monitored. The microscale properties of the ring structure will be observed at the seasonally maximum opening angle of the rings near Solstice. It will allow us to understand time-variability of ring phenomena on decadal timescales. The activity of Saturn's magnetosphere most likely correlates with the

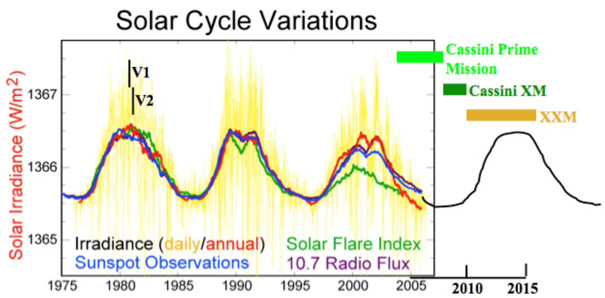

Figure L.1-3. *Solar Cycle Variations with Cassini's Prime, Equinox, and proposed 7-year extended, extended missions, as well as Voyager 1 and 2 flybys.*

11 years solar cycle. The CSM will allow observations of the variations in Saturn's magnetosphere and a better understanding the processes driving its evolution over a solar cycle.

L.2 Setting the Stage for the Next Flagship Mission to Titan

Any future Titan surface mission would benefit from increased high-resolution surface imaging. At the end of Cassini's Prime and Equinox Missions, about 70 Titan flybys will have been obtained and roughly 30% of the surface will be imaged at high resolution by the radar. A seven year extended, extended mission with an additional 50 Titan flybys could bring that number up to 50%. **Figure L.2-1** and **Figure L.2-2**. This would assist in identifying landing sites and/or targets of extreme interest. Evidence for surface changes will be carefully examined. If no change is detectable with Cassini instrumentation, requirements for enhanced instrumentation or observation campaigns may be proposed, given that we have solid reasons to expect surface change with the passing seasons.

L.2.1 Defining the Landing Sites

Determining the types, distribution, sizes, and ages of surface units will continue during the CSM. More specifically, the optical instruments will be able to observe the northern hemisphere which was in the winter night during the nominal mission. As it has been proven for the lake in the Southern hemisphere, the Visual and Infrared Mapping Spectrometer (VIMS) can provide unique information on the nature of the lake (confirm their liquid state) and on the composition (Brown et al. 2008).

Looking at the same lake over a long period going from winter solstice to summer solstice will allow understanding of the evolution of this late on seasonal timescales. Depending on the error ellipse, several seas and lakes could be targeted. Monitoring their evolution up to summer solstice will address questions such as the rate of evaporation of the lakes and their change in surface area. Comparing lakes and seas with the optical instrument is expected to show chemical differences that would be most useful to know before deciding on a surface target. The TSSM lander is planned to be released close to Titan's next winter solstice.

L.2.2 Preparing for Exploration by a Montgolfière

Any future Titan aerial *in situ* mission would benefit from extending atmospheric data collection through the summer solstice. Understanding the global circulation, the winds as the seasons change, and the temporal variability and location of the clouds would help in preparing the design of the mission envisioned for the mongolfière. Any inference of rain as Cassini observes through the changing seasons would assist in further defining the environmental requirements on the montgolfière.

L.2.3 Preparing the Instruments and Their Requirements

The Cassini nominal mission has raised many unanswered questions and has provided clear indications of what measurements must be made to answer those questions. For example, the optical instruments have shown their great capability in the infrared wavelengths. However, this capability was not foreseen before the mission and very few opportunities of observing Titan at closest approach (high spatial resolution) have been possible during its nominal mission. Only two high inclination flybys have been obtained (T20 and T38). The CSM will allow for some equatorial flybys during which optical instruments will operate at closest approach and will provide information on the integration times that are necessary in order to fully take advantage of a camera installed on the montgolfière. Additional information on the magnetic field, including flybys below the ionosphere, will also allow scientists to better

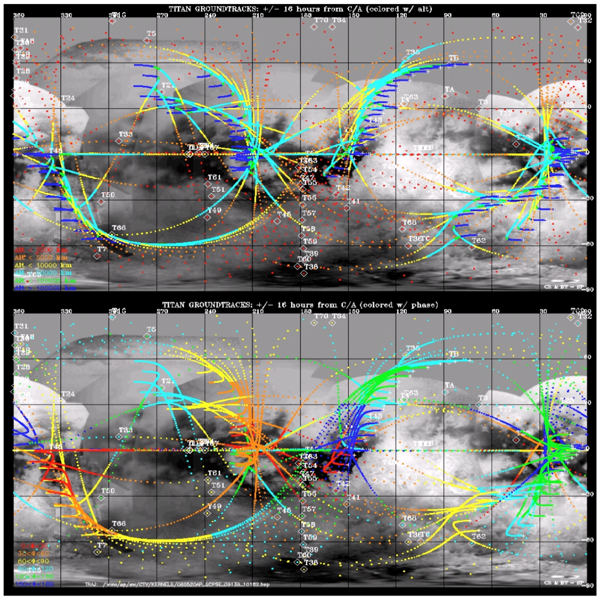

Figure L.2-1. *Titan groundtracks from the Prime and Equinox Missions. Top panel color coded by altitude (red <2500 km, orange <5000 km, yellow <10,000 km, light blue <50,000 km, green <100,000 km, dark blue >100,000 km). The bottom panel color coded by phase (red 0–30 degrees, orange 30–60 degrees, yellow 60–90 degrees, light blue 90–120 degrees, green 120–150 degrees, dark blue 150–180 degrees).*

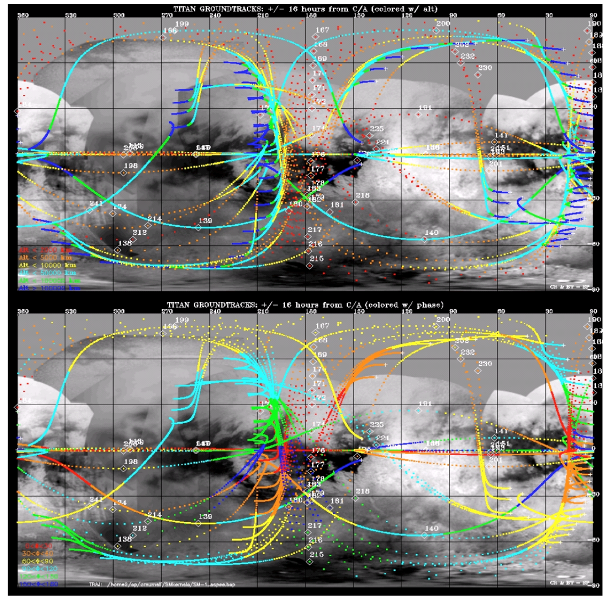

Figure L.2-2. *Titan groundtracks from a representative extended, extended mission. Top panel color coded by altitude (red <2500 km, orange <5000 km, yellow <10,000 km, light blue <50,000 km, green <100,000 km, dark blue >100,000 km]. The bottom panel color coded by phase (red 0–30 degrees, orange 30–60 degrees, yellow 60–90 degrees, light blue 90–120 degrees, green 120–150 degrees, dark blue 150–180 degrees).*

determine the desired characteristics of the magnetometers the orbiter, montgolfière and lander.

L.2.4 Training the Next Generation of People in Charge of the Next Flagship

The nominal plan for CSM has it continuing to 2017, only three years before the Baseline launch date of TSSM. This will provide TSSM with the benefit of personnel that have fresh operations experience with a Saturnian mission. This will also allow for experienced operations personnel to be injected early in the development of TSSM. Personnel with experience in the design of the Cassini Equinox and Solstice missions are already participating in the TSSM study and will be available to participate in the TSSM development starting in Phase A.

The CSM will provide an international science, operations and development capability that could smoothly transition to TSSM, a mission that promises to cover the full range of planetary science disciplines including Geology, Geophysics, Atmospheres, Astrobiology, Chemistry, and Magnetospheres.

M. LETTERS OF SUPPORT AND COMMITMENT

NASA-Glenn M-3
Centre National d'Études Spatiales (CNES) M-4
NASA Astrobiology Institute (NAI) Cooperative Agreement Notice (CAN) Cycle 5 Award Letter M-5
NASA Astrobiology Institute (NAI) M-7

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National Aeronautics and
Space Administration
John H. Glenn Research Center
Lewis Field
Cleveland, OH 44135-3191

September 24, 2008

Reply to Attn of: MA

Mr. Kim R. Reh
Titan Saturn System Mission Study Manager
Jet Propulsion Laboratory
4800 Oak Grove Drive
MS 301-325F
Pasadena, CA 91109

Subject: NASA Glenn Research Center Support to the Titan Saturn System Mission (TSSM)

NASA Glenn Research Center (GRC) was pleased to participate in the Titan Saturn System Mission study. The baseline concept features a Solar Electric Propulsion (SEP) Stage that will implement GRC-developed NEXT thrusters.

We would be honored to partner in the development of the TSSM. GRC is ready to support the electric propulsion system, as well as overall power and propulsion systems for the science spacecraft and SEP Stage. As TSSM progresses and resources become available, you can be confident that GRC will provide the expertise necessary to achieve successful mission confirmation. We look forward to working on the TSSM team.

Sandy Reehorst

Sandra T. Reehorst, Chief
Advanced Flight Projects Office

cc:
M/R. W. Moorehead
MA/S. T. Reehorst
MAS/S. W. Benson

The balloon is a subsystem of the Montgolfière *in situ* element, which is an ESA responsibility.

cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES

Direction de la Prospective, de la Stratégie,
des Programmes, de la Valorisation
et des Relations Internationales
Head, Space Science and Exploration Office

Affaire suivie par : francis.rocard@cnes.fr

Pr. David SOUTHWOOD
Directeur du Programme Scientifique
European Space Agency
8-10 rue Mario Nikis
75738 PARIS cedex 15

Paris, July 16, 2008
DSP/EU - 2008.0017168

Subject: **CNES support to study for the Titan Montgolfiere (TSSM mission)**

Dear Pr Southwood,

Following the selection of the TANDEM proposal, led by Dr. Athena Coustenis from LESIA (CNRS and Observatoire de Paris), as a Cosmic Vision mission candidate, ESA and NASA have carried on the study of a joint mission to the Saturn and Titan system (TSSM).

One element of the mission is a balloon to fly in the Titan atmosphere. In our letter dated June 23, 2007, and signed by my predecessor Richard Bonneville, CNES has announced its intention to provide the balloon envelope and the inflation subsystem. This message is to confirm that should the TSSM proposal be selected jointly by ESA and NASA, CNES would provide these two elements.

To this aim, CNES intends to support the feasibility study of the montgolfiere balloon, including the critical points identified since April 2008 in the frame of the CNES-JPL working group on the montgolfiere design. This group has indeed identified a common design based on a double wall Montgolfiere balloon without an additional He balloon. The feasibility phase covers the development of the balloon fabrication technique, the fabrication of prototypes of balloon systems, the fabrication and demonstration of the packing technique for the cruise phase, the engineering work for the flight physics analysis and the demonstration of the deployment feasibility.

Best regards,

F. Casoli

Fabienne CASOLI

Strategy and Programmes Directorate
Head, Space Science and Exploration Office

Siège : 2 place Maurice Quentin - 75039 Paris cedex 01 - tél. : 33 (0)1 44 76 75 00 - **www.cnes.fr**
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Centre spatial guyanais : BP 726 – 97387 Kourou cedex - tél. : 33 (0)5 94 33 51 11

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National Aeronautics and Space Administration

Headquarters
Washington, DC 20546-0001

October 2, 2008

Reply to Attn of:
Science Mission Directorate

Dr. Mark Allen
Science Division
NASA Jet Propulsion Laboratory
4800 Oak Grove Dr.
Pasadena, CA 91109

Dear Dr. Allen,

We have completed the review and evaluation of proposals submitted in response to the NASA Astrobiology Institute (NAI) Cooperative Agreement Cycle-5 (NNH08ZDA002C). We are pleased to inform you that your proposal entitled "Titan as a Prebiotic Chemical System" (NASA proposal number 08-NAI5-0030) has been selected for funding.

Thirty-seven complete proposals were received in response to the announcement. Each proposal was evaluated by a review panel of peer scientists from academic and government institutions. The process included mail-in reviews and an in-person Review Panel meeting. The meeting included both multidisciplinary sub-panel review and focused discipline-based breakout sessions. The Director of the NAI developed a selection recommendation based on these evaluations. This recommendation was presented to the Selecting Official (the Director of the Planetary Science Division of the Science Mission Directorate at NASA Headquarters) who made the selection decision. The consensus evaluation for your proposal is attached. The Education & Public Outreach elements of each proposal were evaluated by a separate review panel in a comparable process. The final E/PO evaluation is also attached.

Because of limitations on the funds available, you may be required to provide a revised budget profile and statement of work. We will be in touch shortly with information about the final award level, and whether a revised budget and statement of work will be required. In either case, to initiate the award you will have to submit the final budget, research summary, and a signed cover-page (originating from your institution's Grants/Business Office) to the NASA Ames Grants Office.

A total of 10 teams have been selected in this highly competitive process. We congratulate you and your colleagues on your deserved success. Since its inception ten years ago, the NASA Astrobiology Institute and its members have made significant scientific contributions to the field of astrobiology. The Institute has also made progress in forging an interdisciplinary astrobiology community. As the Institute enters its second decade, we look

forward to drawing on your experience, knowledge, and commitment to advancing the field of astrobiology.

Sincerely,

James L. Green
Director, Planetary Science Division
Science Mission Directorate, NASA HQ
Washington, DC
(202) 358-1588

Carl B. Pilcher
Director, NASA Astrobiology Institute
NASA Ames Research Center
Moffett Field, CA
(650) 604-0022

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, CA 94035-1000

September 22, 2008

Professor Jonathan Lunine
Co-chair, Titan Saturn System Mission Study
Lunar and Planetary Laboratory
University of Arizona
1629 E University Blvd.
Tucson AZ 85721

Dear Jonathan,

In its December 12, 2001, letter to Dr. Michael Belton, Chair of the National Research Council (NRC) Steering Committee developing the decadal strategy for Solar System Exploration, the NASA Astrobiology Institute (NAI) Executive Council (EC) included Titan as a target in its list of highest-priority missions for astrobiology. The EC stated that Titan was in the same highest-priority category as Europa with no further prioritization stated or implied. Although Cassini data had not yet been obtained, the expectation was that its receipt would support Titan staying in that highest-priority category. Roughly three years subsequent to that letter the Cassini Orbiter began operations around Saturn and the Huygens probe was delivered through the atmosphere and to the surface of Titan. The data returned by the Cassini-Huygens mission strengthens the notion that Titan is of high astrobiological interest. The composition of Titan's atmosphere and the presence of organic, liquid lakes on the surface (recently confirmed by VIMS spectra) make it a "…priority target for future exploration missions….".[1]

As we understand the current concept for the Titan Saturn System Mission (TSSM), the mission design provides an excellent match for and even exceeds the measurement objectives identified for targets of high astrobiological potential. In particular, in addition to remote sensing, it would carry out in situ measurements of organic and other molecules in Titan's atmosphere and on its surface. The mission would also make flybys of Enceladus, characterizing in more detail the organic material emitted from its plumes and making further observations to constrain whether the source region of the plumes might contain liquid water.

The study commissioned by the NRC's Committee on the Origin and Evolution of Life entitled "The Limits of Organic Life in Planetary Systems"[2] states: "Thus the environment of Titan meets the absolute requirements for life. Titan is not at thermodynamic equilibrium. It has abundant carbon-containing molecules and heteroatoms and a fluid environment. Titan's temperature is low enough to permit a wide range of

[1] Raulin, F., **Organic lakes on Titan**, Nature 454, 587-589 (31 July 2008).
[2] The Limits of Organic Life in Planetary Systems. National Academies Press, 2007.

bonding, covalent and noncovalent. Titan undoubtedly offers other resources believed to be useful for catalysis necessary for life, including metals and surfaces." Clearly, exploring this hypothesis about Titan would provide key astrobiological information as well as points of reference in understanding its differences from the Earth.

In view of these considerations the NAI Executive Council reaffirms Titan to be in the list of highest priority astrobiological targets in the solar system, alongside Europa, and for a mission to Titan and the Saturn System to be in its highest-priority mission category.

Sincerely,

Carl Pilcher

Carl Pilcher, Director of the NAI
for the NAI Executive Council

N. COMPLIANCE MATRIX

Details not available for public release.

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